An Attribute Approach To The Measurement Of Manufacturing System Flexibility

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Declaration

This thesis is presented in accordance with the regulation for the degree of doctor of philosophy. All work reported has been carried out by the author unless otherwise stated.

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Abstract

An uncertain environment has forced manufacturing systems to have flexibility. Uncertainties involved with internal and external factors means that flexibility becomes an important competitive factor for the firms. However, the concept of manufacturing flexibility has not yet been clearly identified, understood and integrated. These problems have led to researchers and practitioners getting confused and this produces difficulties when trying to implement it.

The research in this thesis attempts to clarify and integrate the various aspects of manufacturing flexibility measurement. The objective of the research was to develop theoretical models to quantify the measurement with mathematical mechanisms. A consolidated and synthesized approach, defined as the **attribute approach** is proposed in this thesis. This leads to a unified framework for flexibility measurement.

Vague concepts together with arbitrarily used terminology has led to confusion in concept and contradictions in manufacturing flexibility research. Omissions that appeared in the literature have been identified and remedied in this research. Ten types of flexibility attributes have been proposed and applied to six types of manufacturing flexibility. By exploring of all ten types of flexibility attribute, it has been possible to clarify the confused arguments found in the literature.

The main advantage of the attribute approach is its thorough treatment of flexibility measurement. It has provided a conceptually understandable and theoretically precise method of measuring manufacturing flexibility. It also points to new directions for further research in this field. It is hoped that this thesis has pushed forward the frontier of knowledge in this field.

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Chapter 1

Introduction

1.1 Introduction

Since the 1980s, the manufacturing environment has changed tremendously. Mass production which was induced by standardization and specialization has been replaced by the following conditions:

(1) Reduction in production batch size: production is adopting a more fluid style. This means that the batch size in production and transfer inevitably approach unity.

(2) Product differentiation: due to the variety of customer requirements, products require a variety of specifications.

(3) Reduction in delivery time: market competition has become more vigorous than ever before. The factor of time has become a major issue in manufacturing management.

(4) Reduction in the product life cycle: product design and process design have become more important, and concurrent engineering has improved co-operation between design engineers and manufacturing engineers.

Although manufacturing flexibility has been recognized as a vital competitive advantage (DeMyer et al., 1989), co-existent with cost, quality and time, managers still seem to find it hard to develop this as a tool for competition, due to the difficulty of its measurement (Upton, 1995; Chung and Chen, 1996). Unlike other competitive edges, there is no unified framework to quantify the flexibility and measure it. It will not be possible to set up flexibility as a strategic objective of a manufacturing system if the concept remains in managers' minds rather than in operational applications. Moreover, as there exists a gap between the technique for flexibility assessment and its strategic value, it is insufficient for managers to apply it as a tool to make decisions on investment (Chen et al. 1992).

In order to apply the very concept of flexibility in a manufacturing system downward to the operational level, it is necessary to have a clear perception of what has changed in the current environment and why it is important for a manufacturing system to be able to compete in the current dynamic environment by the use of flexible manufacturing. It is also necessary to recognize the meaning of flexibility and its relationships with the environment and company objectives.

1.2 Thesis organization

The methodology of this thesis follows the procedure in Figure 1.1.

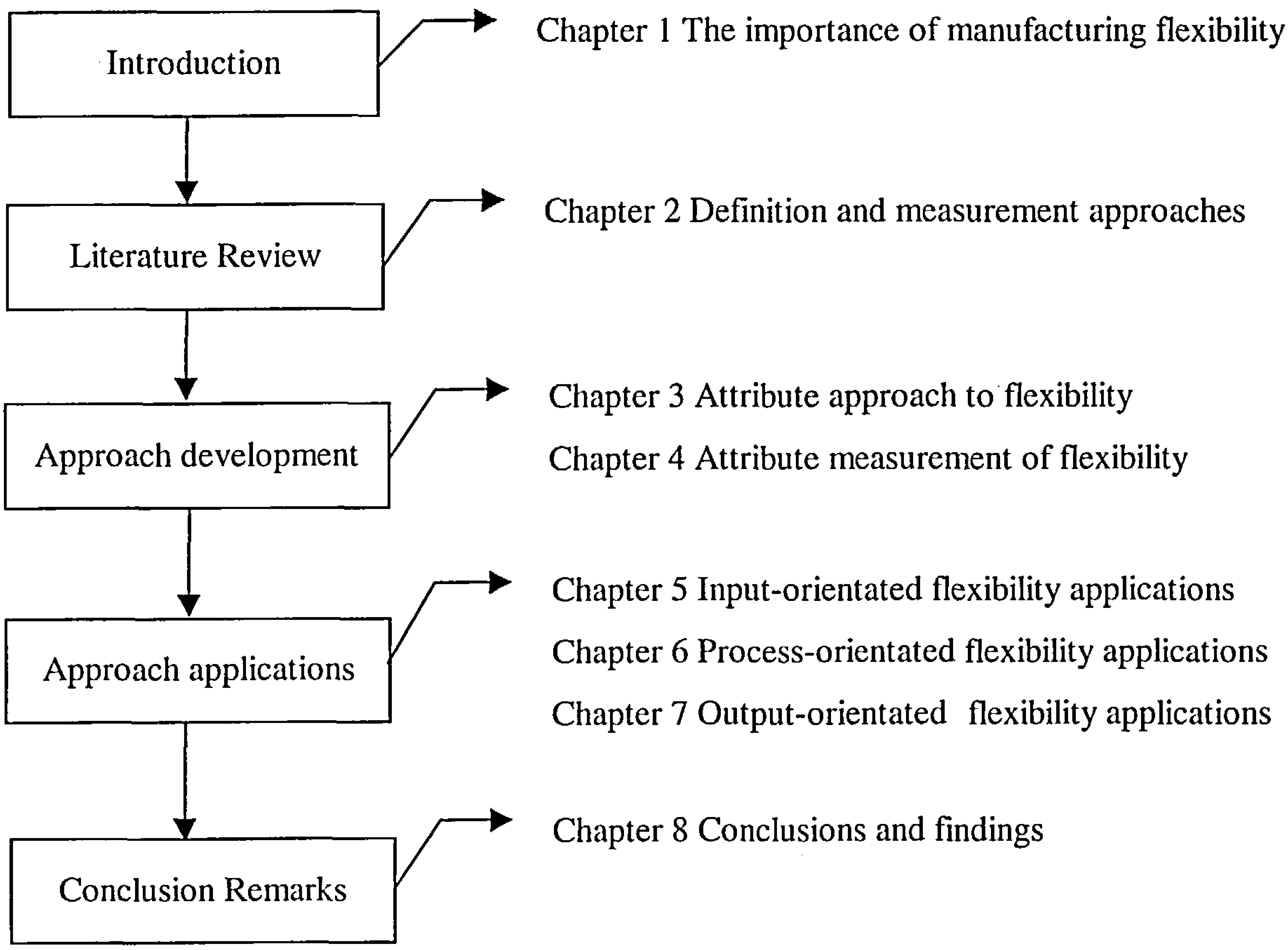


Figure 1.1: A research framework to this thesis

The core issue in Chapter 1 is mainly focused on the discussion why manufacturing flexibility is important for the firms to compete in the current dynamic environment. Failure to recognize the importance of flexibility of manufacturing systems will prevent companies making changes in manufacturing structure (Slack, 1989). A framework to understand the flexibility surroundings has been proposed by this thesis. It includes the changes which occur in the current environment, the meaning and importance of manufacturing flexibility from the viewpoint of environmental changes, a brief description of flexibility types classified by an input-process-output (IPO) demonstration, and an exploration of the relationship between flexibility types and environmental uncertainties and the relationship between manufacturing flexibility and manufacturing objectives.

In Chapter 2, a review of manufacturing flexibility is carried out. The content includes a review of the aspects of manufacturing flexibility which have been investigated in the literature. These aspects are (1) the flexibility typologies with definitions and a classifications with time scale, a hierarchical structure, and a Input-Process-Output (IPO) scheme; (2) a discussions of flexibility measurement approaches; (3) the methodology development of the measurements with dimensional approach, (4) a discussion of flexibility needs, (5) an extension framework of manufacturing flexibility research to include flexibility attribute; and (6) the relationship between flexibility attributes and different system levels.

Chapter 3 proposes a new aspect of manufacturing flexibility research. An attribute scheme of flexibility in manufacturing is explored. The scheme of attributes includes three types of characteristics, namely physical characteristics, managerial characteristics and decision characteristics. The physical attributes are further divided into basic attributes, efficiency and versatility, and supportive attributes, redundancy, variety, mobility and autonomy. The managerial attributes encompass system improvement attributes, learning and control, and decision attributes, weights of importance of output tasks and probability occurrence of the tasks.

Chapter 4 reviews the literature associated with the proposed attributes and suggests the flexibility measurement models for those attributes, except for managerial attributes. The concepts, methods and models of the attributes are all demonstrated respectively. The relationships among the attributes are also indicated.

Chapter 5 applies the developed attributes with mathematical models to the different system levels, namely single resource level and identical group resource level. Firstly, the basic attributes, namely efficiency and versatility, have been applied to the flexibility measurement at single resource level. An example of single machine flexibility has been illustrated. Secondly, resource group flexibility measurement model are suggested by three attributes, namely, efficiency, versatility and redundancy. Machine group flexibility has been demonstrated as the example.

Chapter 6 and Chapter 7 propose measurement models with the attributes for process-orientated types, including routing flexibility and process flexibility, and output-orientated types, including production flexibility and volume flexibility, of manufacturing flexibility.

In Chapter 8, the concluding remarks will specify the findings and contributions of this thesis. Some possible further research in the future has been suggested.

1.3 General description of the manufacturing environment

1.3.1 The changes in enterprise competition

In the post-industrial revolution age, the concept of mass production has led manufacturing to concentrate on production efficiency. It increased industrial development and economic growth. After the 1980's, however, because of changes in the competitive environment, companies have also changed their production strategy and this has created the following issues:

(1) Departure from price-based competition

Since the end of the cold war, defence budgets have been cut greatly, so national economic growth has depended on consumer industries, and consumer goods industries have become the major factor in competitiveness. Since the 1980's, companies in consumer goods industries have faced the following environmental market characteristics: vigorous competition, market segmentation, reduction of the product life cycle, increasing product variation and complicated consumer demands. Based on these characteristics, the major task in the competitive model of the company is no longer to pursue mass production to reduce cost. Companies have now changed their competitive advantage from economies of scale based on price competition to the competition of variation, the so called economies of scope (Goldhar and Jelinek, 1983).

(2) Competitive basis change - from quality to flexibility

DeMeyer et al. (1989) investigated 500 North American, European and Japanese manufacturing managers. They found that companies in Japan set the introduction of new products and the adjustment of production volume as their second and fourth competitive priorities respectively, and quality as the third priority. However, North America and Europe set those two kinds of flexibility as their sixth and eighth priorities respectively and set quality as the first priority. It seems that Japanese companies, after overcoming quality problems, have turned their attention to pursuing flexibility, whereas, Western companies still concentrate on quality (Gerwin, 1993).

Wharton and White (1988) investigated Minnesota manufacturing companies in a mail survey and discovered that unpredictable market change and increasing competition made them seek manufacturing process flexibility. Swamidass and Newell (1987) studied the relationship between environmental uncertainty, strategy and performance and set flexibility as a strategy variable, then they obtained a significant positive relationship between environmental uncertainty and strategy, and between strategy and performance.

1.3.2 The change in the manufacturing environment

In the past, mass production, which focused on standardization and specialization, was the major manufacturing task that could lead to *economies of scale*. Therefore, companies adopted the repeated type of batch production, emphasized the learning effect and line balancing, kept the equipment running and reduced changes as much as possible for high stability to reduce unit production cost; moreover, they stocked inventory to cope with the fluctuation of the production line and customer demand (Goldhar and Jelinek, 1985).

The environment for manufacturing systems is becoming extremely turbulent in the marketplace. A company needs to develop its own strategy to obtain a competitive edge and hence to maintain its high performance or to improve it on the chosen objectives for competition. Companies, therefore, need some measures other than cost-based competitive orientation for the assessment of their performance.

As managers recognize environmental uncertainty, companies know they should change their manufacturing strategy. Uncertainty factors were thought to come only from unpredictable changes of consumer preference and the intense competition of the market. However, Muramatsu et al. (1985) have summarized that uncertainty includes the following factors:

(1) Market change: due to the change of customers' demands, products should be renewed continuously, market demand will fluctuate and the product life cycle will be reduced. Because of greater market segmentation, more kinds of product specification will be needed. Market change has been characterized by the following features:

a. an increasing rate of new product specifications

b. the rate of introduction of new products to the market

c. the length of the product life cycle

(2) Production technology revolution: because of the progress of produ

production line and product specification generate variations quick

the variation of parts shapes and promote the precision and veloc

The development of technology has contributed to the following fe...

a. the reduced interval between the application of new production techniques

b. the changed rate of specifications of parts

c. the improved precision of equipment

d. the increased speed of equipment

e. the reduced interval between the introduction of new materials

1.3.3 The future needs of manufacturing systems

People once believed that the requirements for operating a company efficiently were a huge factory, proper production scale, hard workers and specialized staff, but now they still can not avoid facing the pressure of market competition, the reduction of the product life cycle and the decrease of order size. Therefore, there is a requirement to improve product quality, reliability, innovation, skills and the quality of work life (Skinner, 1985; Hayes and Wheelwright, 1984; Gupta and Goyal, 1989). If it is necessary for a company to surmount sales and marketing difficulties, it should introduce flexibility into its manufacturing systems. Pursuing flexibility will generate a tremendous impact on manufacturing systems. One of the objectives is to find the impact.

(1) The issue of a trade-off between flexibility and cost-efficiency

DeMeyer (1986) stated that in the period 1975-1985 Japanese companies overcame the trade-off between quality and cost-efficiency, meaning that Japanese companies broke the constraint of sacrificing cost in order to promote their quality level. Quality consequently became the competitive advantage in the 80's. DeMeyer et al. (1989) discovered that flexibility need not be at the expense of cost effectiveness. In the future competitive environment industry will be able to overcome the old pattern of trading-off flexibility against cost-efficiency (Hyun and Ahn, 1992).

Slack (1989) drew a similar conclusion that there should be no trade-off between cost-efficiency and flexibility in the period 1985-1995, meaning that it is not necessary to pay more to do different things and implying that the constraints have been overcome by advanced companies, not only by means of advanced technology but also by the newer theories of production management. Aware of the overwhelming quality of the products of Japanese companies, they are in turn focusing on overcoming the variety of needs of their customers; and as a result, flexibility is becoming the next factor in competitive advantage.

(2) Restart from equipment selection

Traditional manufacturing depended on the following kinds of equipment:

a. General-purpose equipment: This is suitable for mass production and for one kind of product. Its benefit is to ensure low cost, but there is a lack of flexibility.

b. Machine centres: They can produce varied kinds of product in low volume with low cost and have the adaptability for design change, demand fluctuation and production-mix change.

Gerwin (1993) stated that advanced manufacturing systems have offered a better selection, more flexible than general-purpose equipment and lower unit production costs than machine centres.

However, there is no assurance of becoming more competitive by using new manufacturing technology unless companies also have good management. Jaikumar (1986) reviewed American Flexible Manufacturing Systems and put forward his opinions:

> *...they are buying the hardware of flexible automation - but they are using it very poorly. Rather than narrowing the competitive gap with Japan, the technology of automation is widening it further. With few exceptions, the flexible manufacturing systems installed in the United States show an astonishing lack of flexibility. In many cases, they perform worse than the conventional technology they replaced. The technology itself is not to blame; it is management that makes the difference....*

In summary, the changing consumer market and improving technologies bring environmental uncertainty (Muramatsu et al, 1985). Goldhar and Jelinek (1985) thought it would exhibit a new competitive model in manufacturing strategy, which needs not only flexible automation technologies, but flexibility management to achieve the following objectives:

(1) Diversified products: varied and personalized customer choice, the change of relationship between buyers and sellers, and consumer preferences have reduced the

loyalty of consumers to specific products. Market strategy, which emphasized increasing market share in the past, will turn its orientation to gaining many competitive niches based on segmenting the markets. So, they need to increase the kinds of product specification.

(2) Decreased production batch size: following the change of environment, production type will turn from batch production to flow production type and one piece transferring production type. This means the batch size of production and transfer will approach one, "one-at-a-time and one-of-a-kind".

(3) Reduced delivery time: market competition tends to become more vigorous and reducing in time becomes a major problem. Just-in-time and zero inventory production will lead to the concept of zero time. This will result in the following objectives: zero learning time for workers, zero setup time for machines, zero residence times for raw materials, zero rework times, and zero information transfer time. The objective of zero time is clearly a conceptual, rather than a practical target; however, it does help to establish the aim of never ending improvement towards a real minimum.

(4) Increased equipment availability time: for the efficient operation of the system and avoid equipment breakdown, a company should concentrate on the planning and carrying out of total productive maintenance.

1.4 A manufacturing flexibility framework

In order to have a clear idea of manufacturing flexibility, Gerwin's (1993) framework is an excellent way to obtain the whole picture of flexibility in manufacturing. Gerwin combined the ideas of Child (1972) and Skinner (1985) into the following conceptual framework (Figure 1.2):

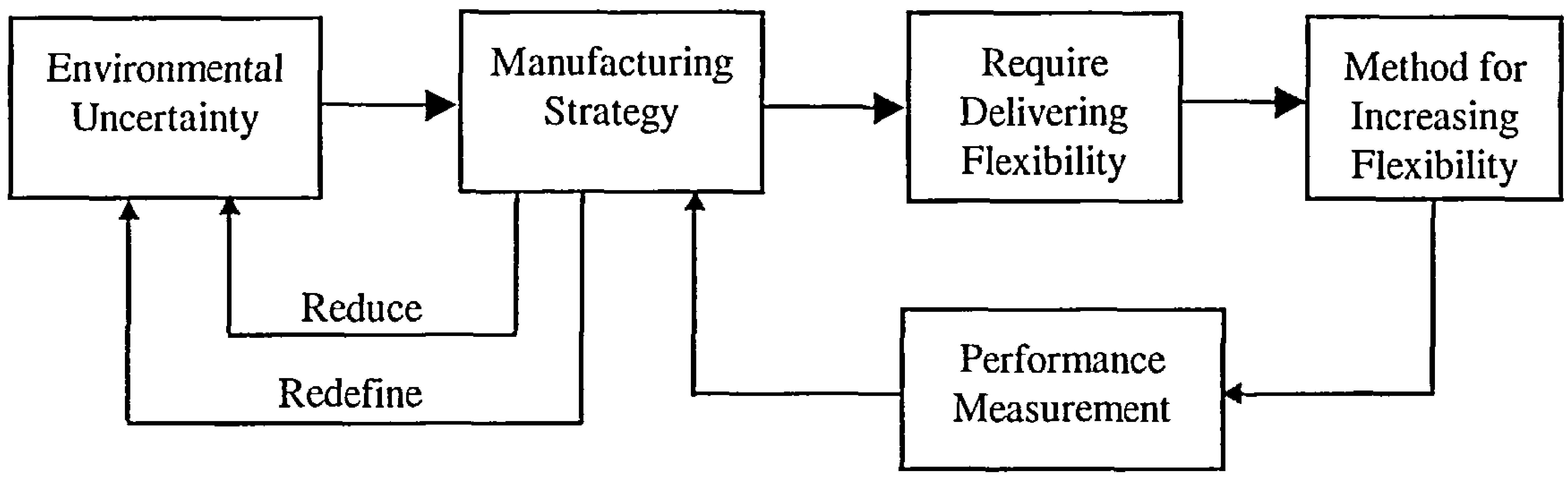


Figure 1.2: Gerwin's (1993) conceptual framework of manufacturing flexibility

In Figure 1.2, the conceptual framework demonstrates the relationship between manufacturing flexibility and environmental uncertainty, and the relationship between manufacturing strategy and performance measurement. For a better understanding, the method applied by the author in this thesis has slightly changed and expanded the framework shown in Figure 1.3.

Figure 1.3 shows that manufacturing flexibility is the core of the framework and is needed as environmental uncertainties are encountered. As a factor in manufacturing strategy, manufacturing flexibility can be implemented as adaptation, redefinition, banking and reduction roles to face uncertainties, internally and externally. According to the requirements of the system, it is necessary to adjust the method of delivering flexibility for strategic implementation and hence to improve the performance of manufacturing.

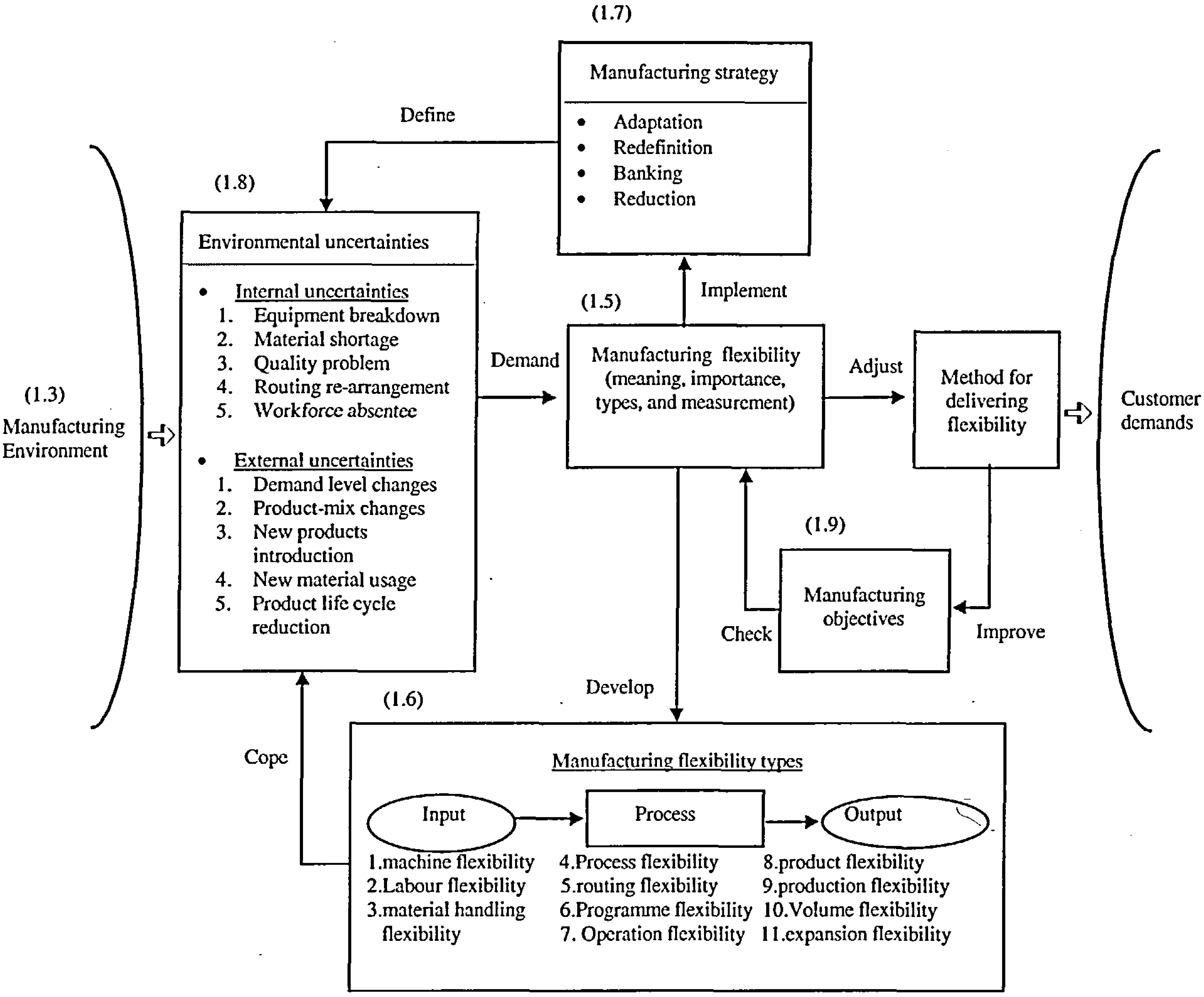


Figure 1.3: An expanded framework of manufacturing flexibility

Following the description indicated in Figure 1.3, the meaning and importance of flexibility, flexibility scope definition, the relationship between manufacturing flexibility and manufacturing objectives, and the relationship between manufacturing flexibility and environmental uncertainty will be introduced respectively.

1.5 Meaning and importance of manufacturing flexibility

1.5.1 Meaning of manufacturing flexibility

Buzacott and Mandlebaum (1985) defined manufacturing flexibility as follows: "*Flexibility of a system is its adaptability to a wide range of possible environments that it may encounter.*" Many researchers have agreed with this definition and quoted it in their papers (Gerwin, 1993; Hyun and Ahn, 1992; Sethi and Sethi, 1990; Brill and Mandelbaum, 1990; Gupta and Goyal, 1989; Cox, 1989; etc).

Kickert's (1985) statement seems slightly different to Buzacott and Mandlebaum (1985). Kickert (1985) said that flexibility indicates the changing forms of control objectives, by way of increasing types, speed and volume to improve the controlability of the system to cope with the evolution of future environmental uncertainty. There were, of course, many explanations and annotations, but most of them were based on the definition stated by Buzacott and Mandelbaum (1985).

Zelenovic (1982) considered that a manufacturing system calls for flexibility in order to cope with different kinds of environment variations and the needs of manufacturing processes capabilities. Hall (1983) stated that flexibility means the quick production changeover from one part or product to another. Gustavsson (1984) defined manufacturing flexibility as the following three aspects: (1) product changes: meaning different kinds of modifications or innovations of part configurations; (2) production system changes: meaning new machines, new production methods, new systems (e.g. computerization); and new operators adding to the system; and (3) demand changes:

meaning fluctuations and unexpected variations on demand. Hayes and Wheelwright (1984) described the flexibility of a system as the ability to change its production volume and/or products. Carter (1986) thought of flexibility as a set of characteristics of a manufacturing system. In this thesis it is proposed that there are multi-attributes within the concept of manufacturing flexibility. Those flexibility attributes should be examined, before proposing the measurement models.

Extending the previous definition, Gupta and Somers (1992) summarized much of the literature to state the following features:

1. Manufacturing flexibility is a complex, multidimensional and difficult concept to synthesize (Sethi and Sethi, 1990), so different researchers have taken different viewpoints and different frameworks for analysis.
2. It is the ability to cope with environmental changes (Mandelbaum, 1978).
3. It was used for dealing with the uncertainty of the environment (Mascarenhas, 1981).
4. It offered an important measurement indicator of total manufacturing performance (Hayes and Wheelwright, 1984; Son and Park, 1987).
5. To pursue flexibility will be one of the important objectives in any manufacturing system (Chatterjee et al., 1984).
6. It ensures obtaining both cost efficiency and flexibility at the same time. In detail, it can reduce setup time, make small batch production reach the effect of mass production, and impel a company's strategy to turn from economies of scale to economies of scope (Goldhar and Jelinck, 1983).

Swamidass (1988) considered that for strategic purposes manufacturing flexibility not only requires the system to react with environmental changes, but also that it proactively adapts itself to change the environment in which it is located. Gerwin (1993) came to a similar conclusion with Swamidass (1988).

Having taken account of all the definitions given in the reports above, this thesis defines manufacturing flexibility as ***a system which can effectively adapt itself to environmental changes intentionally and responsively with a wide variety of tasks.***

1.5.2 Importance of manufacturing flexibility

Researchers have thought that the reason for paying attention to manufacturing flexibility came from the relationship with environmental uncertainty (Gupta and Goyal, 1989). The environment is becoming more and more variable and unpredictable. Therefore, manufacturing systems need flexibility to neutralize these effects.

(1) Playing a competitive edge role in manufacturing strategy

In the future, industrial nations may depend upon flexible manufacturing systems to produce their customized products (Hall and Tonkin, 1990; Nagel and Dove, 1991). Proceeding from this point of view, the only way to compete with low cost and standardized products from foreign countries is to aim at a market niche to offer extensive and diversified products produced by advanced manufacturing systems. Therefore, it is necessary to speed up the application of flexibility to conventional and new industries (Gerwin, 1993).

In the following Table 1.1, the manufacturing strategy objectives are divided into four stages chronologically and integrated with the concept of two criteria - qualifying criteria and order-winning criteria, stated by Hill (1989).

Table 1.1: The revolution of manufacturing strategies

Criteria \ Era	1920's	1950's	1980's	1990's
Winning criteria	Cost	Quality	Flexibility	Time
Qualifying criteria		Cost	Quality + Cost	Flexibility + Quality + Cost

Combining these two criteria with the strategy objectives - *cost*, *quality*, *flexibility* and *time*, it can explain the revolution in manufacturing strategies. The order-winning criterion of Ford was cost in the 1920's. By making great efforts and improvements over a period of time, Ford's competitors were able to reach the *cost* requirement. And then *cost* became a qualifying criterion.

After this, Japanese companies used *quality* as an order-winning criterion and improved their market share. In the 1980s, high quality had become a qualifying criterion. If a company could not reach the *quality* requirement, it would lose its orders. Poor *quality* therefore became an order-losing criterion. From this point of view, if a company does not want to lose its customers, it should at least maintain its qualifying criterion. And if it wants to win orders in the marketplace, it should maintain its order-winning criterion.

Flexibility, in the late 1980s, and *time*, in the 1990s, have become order-winning criteria. And, someday, they will become qualifying criteria. Moreover, if a company can not maintain the ability to achieve qualifying criteria, they in turn become order-losing criteria. So, this is the time to concentrate on the flexibility of the manufacturing systems. If firms can not reach this requirement, they will lose their customers. Moreover, the evolution of manufacturing strategies has entered into the *time* aspect. Research emphasizes that manufacturing systems need a time-based competitive orientation. Therefore, the consideration of a flexible manufacturing should be greatly associated with *time* factors.

Miller and Rath (1987), in a report by the Boston University Manufacturing Round Table, pointed out that flexibility, in future competitiveness, will stand in a very important position, ranked from fourth to eighth for different industries. Although manufacturing flexibility, indicated by Ettlie (1988), has been recognized as an important means of competitiveness in the market, industries do not understand it well (Ramasesh and Jayakumar, 1991).

(2) Decision making linkage

The implementation of flexibility of manufacturing requires strategy orientation and operation orientation. In the former case the purpose of flexibility is to handle environmental uncertainty, while in the latter case it is to design specific methods for the implementations (Gerwin, 1993). With these implementations, it brings the decision makers at different levels together to establish a better way of competing and can also create a good atmosphere within the company.

It has been recognized that manufacturing flexibility types, which will be specified in the next section, are concerned with different levels of a manufacturing system and they affect each other in decision making. Generally, on the one hand, **the lower level of system flexibility is able to sustain the higher level of system flexibility.** In other words, if an organization wants to have flexibility at the system level, it should have flexibility at the resource level. On the other hand, **trade-offs exist between different types of flexibility.** Therefore, it is necessary to bring them together in order to use them as a competitive tool.

(3) Functional department integration

Following the linkage of strategic and operational, the system will be able to link the functional departments, namely the marketing, manufacturing and research and development (R&D) departments.

Conflicts exist between the functional departments of an organization, especially between manufacturing and marketing, and between manufacturing and R&D. Chen et al. (1992) demonstrated that the way of neutralizing conflicts between the former case is to introduce different groups of flexibility - manufacturing-based flexibility and marketing-based flexibility - into the manufacturing system. Those types of flexibility are included in the typologies of manufacturing flexibility. Pursuing manufacturing flexibility will enable the system to concentrate on the importance of communications and cooperation within the manufacturing and marketing departments.

If functional activities are operated independently within the departments, conflicts could also arise between the departments of manufacturing and R&D. One of the objectives for the system is to introduce new products to market efficiently. Conflicts between the two departments cause engineering changes frequently and they will delay the time of new product introduction. Effective cross functional communications, cooperation and integration are necessary to meet this goal.

The improvement of manufacturing flexibility can not just consider the factors within the manufacturing department, otherwise, the results will be limited. The integration with before manufacturing activities and after manufacturing activities in the production system is the way to push the system performances to a higher level of achievement.

1.6 Manufacturing flexibility types

1.6.1 Manufacturing system scope

It is necessary to define the boundary of a manufacturing system in order that the framework of the flexibility measurement in this thesis can be defined. This research suggests that a manufacturing system is defined, from the production process point of view, as the range of activities starting from when the production order is received to when the order is finished. Product design, material purchasing and product delivering should be all excluded.

For example, Suarez et al. (1996)'s point of view is that new product flexibility measurement includes the time of "time-to-market", meaning the time duration from the recognition of the customers' needs to the introduction of the new products into the market. This concept is beyond the boundary of manufacturing flexibility research. The discussion of flexibility in manufacturing systems should be confined to manufacturing related activities and should exclude non-manufacturing activities. The time from launching the design to the completion does not fall within the activity of the manufacturing department. It should only include the time between the completion of the design to the completion of the new product to the market.

1.6.2 Manufacturing flexibility scope

A flexible system is a system which accommodates the ability to cope with customers' preference changes, in terms of product changes and demand fluctuations. To achieve these two goals, it is imperative for the manufacturing system to have the ability to change within the production processes, in terms of process changes, routing changes and programme changes. To accommodate those changes, a manufacturing system needs to have basic flexibility in its resources, namely machines, material handling systems and labour. They are all related to the subjects of manufacturing flexibility. For a better understanding of manufacturing flexibility, there have been many typologies in the literature (Mandelbaum, 1978; Buzacott, 1982; Browne et al., 1984; Gupta and Goyal, 1989; Sethi and Sethi, 1990; Gupta and Somers, 1992; among others).

Sethi and Sethi's (1990) work is the most comprehensive. They divided the types of manufacturing flexibility into 11, namely machine flexibility, material handling flexibility, process flexibility, routing flexibility, operation flexibility, programme flexibility, product flexibility, production flexibility, volume flexibility, expansion flexibility and market flexibility. This thesis suggests that labour flexibility is of vital importance in making a system flexible, and should be included in the research on manufacturing flexibility. However, market flexibility is taken to be outside the boundary developed in this thesis, and therefore should not be included. The detailed definitions and explanations of the 11 types of flexibility will be explored in the next chapter. In addition, their measurement variables will also be specified with three dimensions, namely time, cost and range.

For a better understanding of flexibility types in manufacturing systems, this thesis divides them into groups of an Input-Process-Output (IPO) scheme. Such a classification, in addition, will help managers to recognize by what means system performance will be improved, and how to improve flexibility at different managerial levels, and how to cope with internal or external environmental uncertainties. Figure 1.4 illustrates an input/output model to group the 11 types of flexibility explained above.

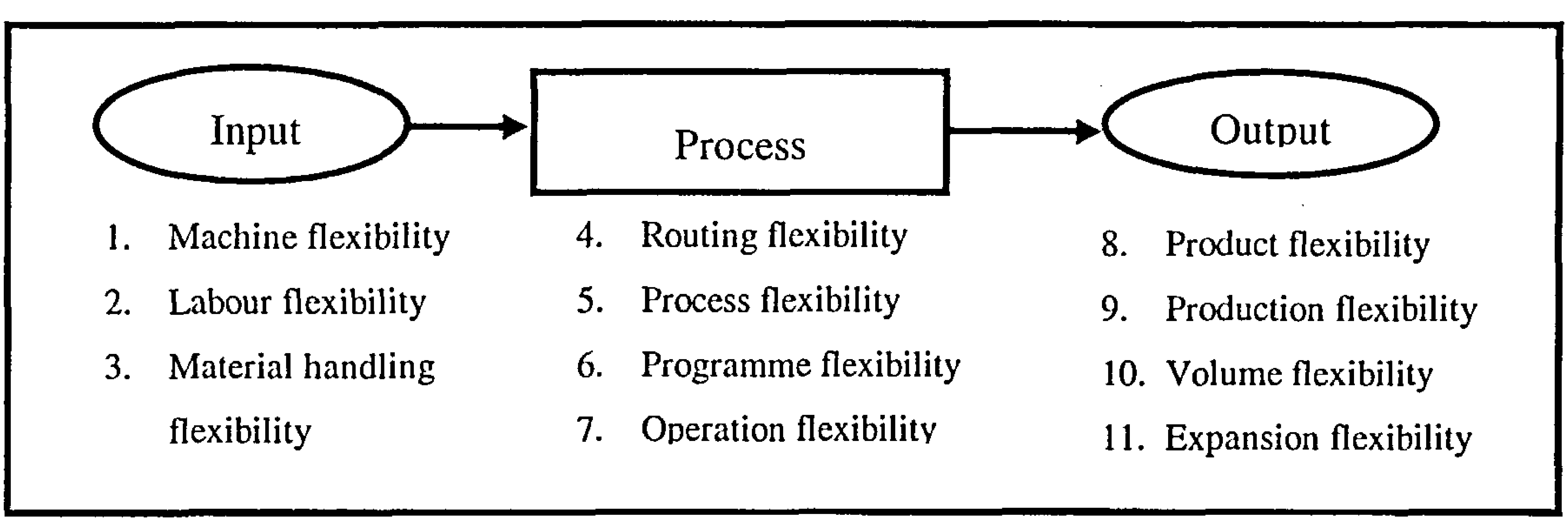


Figure 1.4: An Input-Process-Output classification scheme of flexibility types

1.7 Manufacturing strategy implementation

Gerwin (1993) specified that by implementing flexibility of manufacturing could meet four general strategy requirements, namely adaptation, redefinition, banking and reduction. The importance of manufacturing flexibility is partly delivered form its competitive orientation. Managers have recognized that manufacturing flexibility is important to compete in the marketplace, but the understanding of how to apply flexibility as a competitive edge is spare. The following explanations could help to understand the merit of manufacturing flexibility.

With respect to *adaptation*, it is generally regarded as a defensive approach, in which the system acts as a responsive mechanism to the impacts from environmental uncertainties. Manufacturing flexibility depicts the ability of a system to respond effectively to stimuli from the environment. A general flexible manufacturing system is regarded as the ability to react to the dynamic environments.

The term "*redefinition*" refers to changing the conditions of competition in the marketplace. If the capability of a manufacturing system has been improved, the system is therefore able to offer more benefits, e.g., shorter manufacturing lead time, on-time delivery, the more frequent introduction of new products and a wider variety of alternative products. The new forms of competition will create new customer expectations and in turn change the market needs. It therefore brings uncertainty to its competitors. From a competitive point of view, it plays a proactive role. Manufacturing flexibility in a way is to put pressure on their competitors, because a flexible system embodies the greater ability to introduce new products quickly, switch production process easily and delivery products to customer efficiently.

Banking, according Gerwin (1993), refers to the reserving of certain capabilities to meet future needs. The reservation could be of redundant equipment, workers and computer systems (Hall and Tonkin, 1990). It enhances the system to accommodate defensively the ability to cope with future fluctuation demands or preference changes of customers. A flexible system preserves its potential of production capability and capacity. It improves the system to cope with unpredictable changes in the factory or from marketplaces more properly.

Finally, *reduction*, on the other hand, refers to reducing the need to rely upon flexibility. Proactively the approaches for reduction mainly refer to lessening the uncertainties of the environment. The approach could include: (1) by making good relationships with customers and suppliers to ensure more stable production volume and reliable material and/or components supply; (2) to build a cross functional team and apply design for manufacturing (DFM) and design for assembly (DFA) to reduce engineering changes in production; and (3) to implement total preventive maintenance (TPM) and total quality control (TQC) to ensure equipment availability and product reliability, and so forth (Gerwin, 1993). There are other applicable approaches, including module design, reduction in the number of components within the products, and quick setup techniques (Chang, 1999). **Flexibility is worth to pursue for a manufacturing system, but it is not cheap to obtain. If it is not implemented properly, a company could pay a fortune to get it.**

This thesis explores the manufacturing flexibility in considerable detail. This is a great help to managers to think the advantages of manufacturing flexibility and problems which could be encountered when implementing it.

1.8 Environment

The competitive value of manufacturing flexibility has been recognized as lying in its controllability in the face of uncertain demand (Swamidass, 1985; Swamidass and Newell, 1987). The main reason to call for flexibility of a manufacturing system is to cope with an uncertain environment. Swamidass and Newell (1987) examined the relationships between manufacturing strategy and environmental uncertainty and the relationship between manufacturing strategy and performance with an open loop model. In the model manufacturing flexibility was treated as a factor of manufacturing strategy. They concluded that there is a positive relationship between flexibility and performance and that it is necessary for a manufacturing system to have flexibility to cope with an uncertain environment.

Uncertain factors come from two areas, namely internal and external. The former includes: equipment breakdowns, variable task times, queuing delays, rejects, and reworks (Buzacott and Mandelbaum, 1985). **While, the latter includes: changes or fluctuations in level of demand, product price change, product mix change, and action of competitors** (Garrett, 1986; Gupta and Goyal, 1992; Zelenovic, 1982). Figure1.5 illustrates a system when it encounters environmental uncertainties from inside and outside the system. A flexible system is one which has the ability to cope with them.

In Figure 1.5, when the uncertainties arise from inside the system, there are input-orientated types of flexibility, namely machine flexibility, labour flexibility and material handling flexibility, and process-orientated types of flexibility, namely process flexibility, routing flexibility and programme flexibility. Whereas, for the external uncertainties, output-orientated types of flexibility, namely product flexibility, production flexibility, volume flexibility and expansion flexibility, are ready for coping with them.

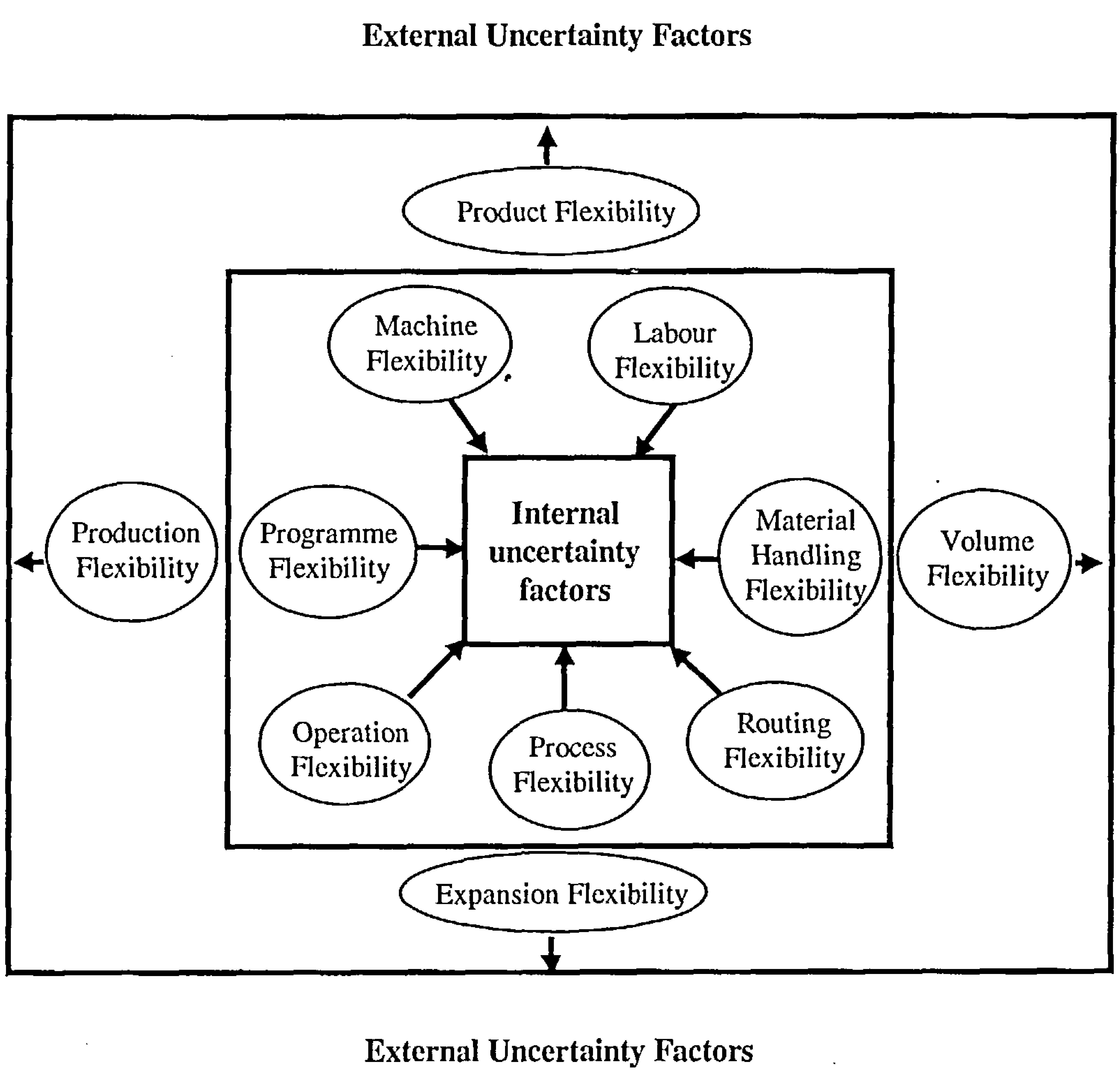


Figure 1.5: Manufacturing flexibility types and environmental uncertainties

1.9 Manufacturing objectives

Researchers (Swamidass and Newell, 1987) have discovered that the more flexible the system, the better the performance. As many objectives of a manufacturing system can be identified as are needed. A manager can choose those factors that are suitable to focus the system's effort and to achieve its strategic goals, when the system is involved in different circumstances. For two extreme examples, a homogenous vast market needs a mass production system, while for variant and segmented markets, it is necessary to have a flexible system.

Slack (1989) stated that the first order objectives of a flexible system should be to have the following three abilities, namely availability, reliability and productivity. The first order objectives proposed by Slack (1989) are associated with the things which customers are really concerned about. Customers demand the availability of new products, different product-mixes and volumes, reliable delivery, on time delivery, and low cost to produce the products.

However, customers do not expect to spend money to pay for the flexibility of a system. Therefore, Slack (1989) pointed out that flexibility is a second order objective, which means it is for supporting the first objectives. The author in this thesis states that the first order objectives are market orientated, while the second order objective is manufacturing orientated.

Figure 1.6 depicts the relationships between the first and second order objectives in a flexible system. Acting as a second order objective, the flexibility of a system is supported by the following manufacturing related criteria:

1.Quick changeover time

2.Short production lead time

3.Little waste

4.Low inventory

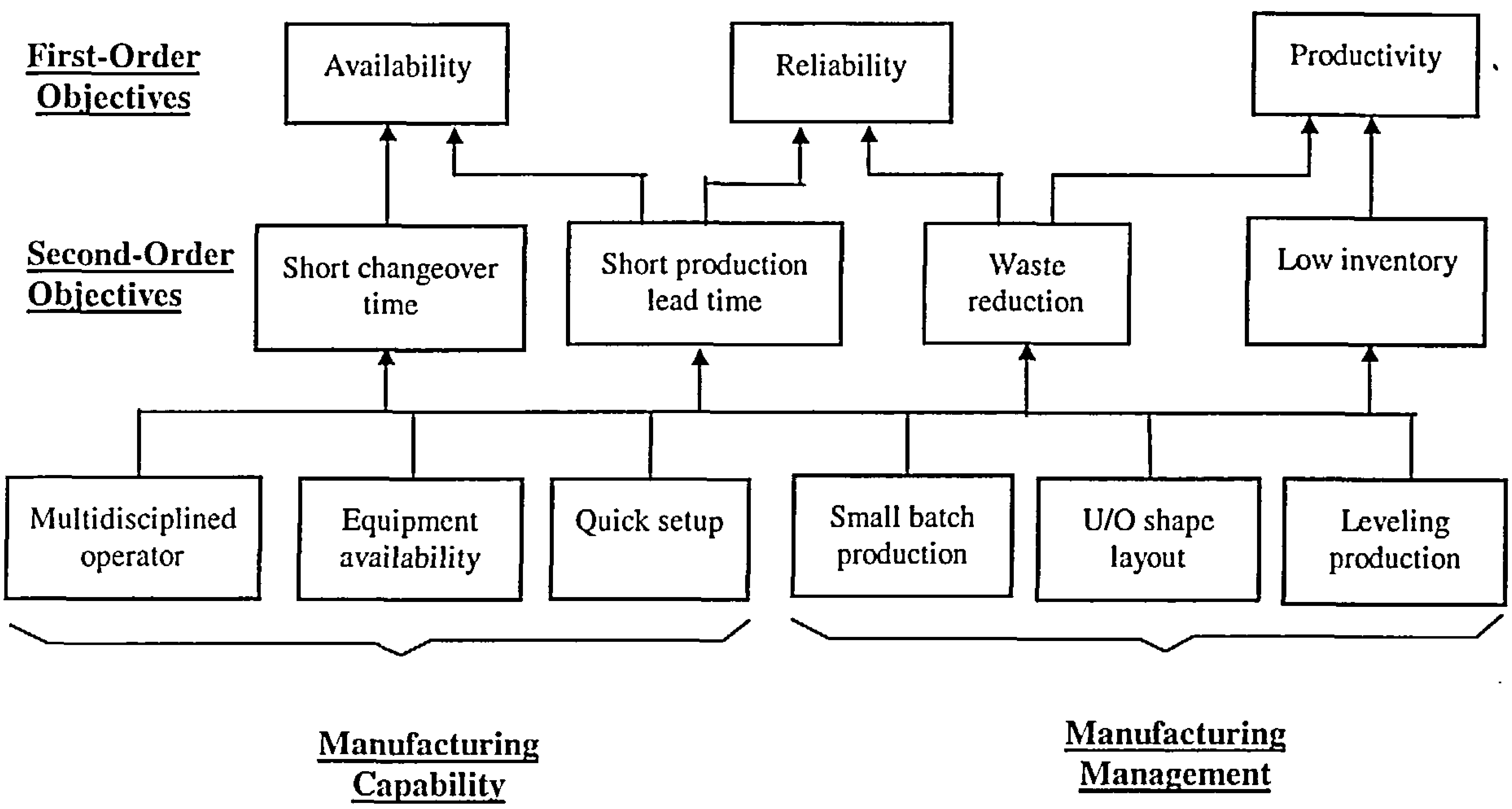


Figure 1.6: The objectives of a flexible manufacturing system

The ability to achieve quick changeover ensures a system can supply new products quickly, change product mix swiftly and accommodate volume variations easily. It therefore shows the system is readily available to supply different customers with demand changes and fluctuations. The availability of a system calls not just for quick changeover, but also for short production lead time, the time from when the order is received to when it is finished. Furthermore, for achieving the second order objective, a flexible system needs to have two types of manufacturing abilities, namely manufacturing capability and manufacturing management. The former includes multidisciplined operators, high equipment availability and quick setup for necessary changeovers, while the latter includes U or O shape production lines (U or O shape facilities layout), small production (process and transfer) batch size and leveling production (Monden, 1993).

1.10 Concluding Remarks

1.10.1 Research purposes and objectives

(1) Research purposes

The importance of flexibility in manufacturing systems has been recognized as a vital factor in market competition. Nevertheless, in practice, flexibility in the manufacturing system still remains in managers' minds, not in daily operational activities. Also, confusion and contradictions exist in the theory, as proposed in the measurement approaches in the literature.

Manufacturing flexibility embodies multi-dimensional attributes and is a complicated manufacturing performance objective. Researchers have claimed that it is hard to give an integrated treatment when measuring it, and it is difficult to implement it in practice. Therefore, it is worthwhile to give a thorough examination of the concept of flexibility and to inspect the approaches proposed in the literature. The methodology for a more reasonable measurement approach of manufacturing flexibility should be explored and consequently the measurement models need to be made more specific.

Like quality in the 50's or 60's, flexibility remains unspecified. It is definitely worthwhile to do a further detailed study into the field of manufacturing flexibility (Upton, 1995).

(2) Research objectives

The objectives of this thesis are as follows:

1. to give a clear picture of manufacturing flexibility, a framework specification;
2. to specify the surrounding aspects of manufacturing flexibility in the literature, in terms of 11 types of classification with definitions and measurement approaches from the point of view of three dimensions, namely time, cost and range; the other aspects related to manufacturing flexibility in terms of flexibility needs;
3. to examine the attributes embodied in the concept of flexibility in manufacturing systems and propose measurement models for the attributes; and
4. to construct the measurement models from the viewpoint of attribute considerations to measure manufacturing system flexibility at different system levels and with different flexibility types.

1.10.2 Research scope and constraints

Gerwin (1986) stated that it is vitally important to define the domain or boundaries of the system when it is measured. In the surveyed literature, it can be seen that the authors seemed failed to identify what was the boundary when measuring a particular type of flexibility or which level of the organization it applied for. He further addressed that the different domains of the flexibility concept might vary at different levels, as it could be alternative means to achieve flexibility of the system.

Upton (1994) pointed out that the vague situation in the literature concerning manufacturing flexibility is partly due to an unclear definition given to the measured system level or flexibility type correspondingly. For example, when talking about product flexibility, meaning supply variety of alternative products to the customers, it was proposed that the firm could rely on its procurement activities in stead of producing them. Moreover, the system reduces the pressure caused by changing production line, quick response and demand fluctuations by stock inventories. These two examples should not be considered as the manufacturing abilities of the system, and hence could not be included in the research scope of manufacturing flexibility. The former example shows that the ability is not supported by its own manufacturing capability, but by its suppliers. The latter example actually shows the deficiency of the system.

The work in this thesis is focused on a general manufacturing system, specifically a plant, which gathers a number of different types of resources and produces a wide variety of outputs, a set of parts or products. More generally, the field in this research is confined within the activities associated with manufacturing in the system. Product design activity, material procurements and product sale, for example, will not be included in the scope of this research. Consequently, the performance indicators should reveal the actual output from manufacturing activities, e.g., cost, quality, throughput, yield, work-in-progress (WIP), productivity and so forth, rather than profit, market share, or return on assets, etc. Although the latter embody the major concern for managers, it seems unreasonable to say that the entire contribution is created by manufacturing activities. Marketing, at least, is another contributor to those financial performances of the firm.

This thesis will not include the whole area associated with the subjects of manufacturing flexibility. Rather, this research will focus on aiming at proposing the measurement models of manufacturing flexibility for operational applications, due to the fact that more analytical measurement work needs to be done in this area (Sethi and Sethi, 1990; Ramasesh and Jayakumar, 1991, Gerwin, 1993; among others). Therefore, the intentions of this research are to propose mathematical models for application at different system levels and on different types of manufacturing flexibility in practice.

1.11 References

Brill, P. H. and Mandelbaum, M. (1990), "Measurement of Adaptivity and Flexibility in Production Systems", *European Journal of Operational Research*, 49, pp.325-332.

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P., and Stecke, K. E. (1984), "Classification of Flexible Manufacturing Systems", *The FMS Magazine*, 2 (2), pp.114-117.

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the 1st International Conference on FMSs*, Brighton, UK, pp.13-22.

Buzacott, J. and Mandelbaum, M. (1985), "Flexibility and Productivity in Manufacturing Systems", in *Proceedings of the IIE Conference*, (Chicago, IL), Industrial Engineering and Management Press, Atlanta, CCA, pp.404-413.

Chang, S. L. (1999), *Excellence Production Management - from Just-In-Time to World Class Manufacturing*, Hwa Ti, Taipei.

Chatterjee, A., Cohen, M. A., Maxwell, W. L. and Miller, L. W. (1984), "Manufacturing Flexibility: Models and Measurements", in *Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.49-64.

Chen, I. J., Calantone, R. J. and Chung, C. H. (1992), "The Marketing-Manufacturing

Interface and Manufacturing Flexibility. *OMEGA*, 20 (4), pp.114-117.

Child, J. (1972), "Organizational Structure, Environment and Performance: The Role of Strategic Choice", *Sociology*, 6, pp.1-22.

Chung, C. H. and Chen, I. J. (1996), "An Examination of Flexibility Measurements and Performance of Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 34, no. 2, pp.379-394.

Cox, J. T. (1989), "Toward the Measurement of Manufacturing Flexibility", *Production and Inventory Management Journal*, First Quarter, pp.68-72.

DeMeyer, A., Nakane, J., Miller, J. and Ferdows, K. (1989), "Flexibility: The Next Competitive Battle, The Manufacturing Future Survey." *Strategic Management Journal*, Vol. 10, pp.135-144.

Ettile, J. E. (1988), "Implementation Strategies for Discrete Parts Manufacturing Technologies: Final NSF Report", University of Michigan (Ann Arbor, MI: University of Michigan).

Garrett, S. E. (1986), "Strategy First: A Case in FMS Justification", in, *Proceedings of the 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.17-30.

Gerwin, D. (1987), " An Agenda for Research on the Flexibility of Manufacturing Processes", *International Journal of Production Management*, Vol. 7, No. 1, pp38-49.

Gerwin, D. (1993), "Manufacturing Flexibility: A Strategic Perspective", *Management Science*, Vol. 39, No. 4, pp.395-410.

Goldhar, J. D. and Jelinek, M. (1983), "Plan for Economies of Scope", *Harvard Business Review*, Nov.-Dec., pp.88-94.

Goldhar, J. D. and Jelinek, M. (1985), "Computer Integrated Flexible Manufacturing: Organizational, Economic, and Strategic Implications", *Interface*, 15(3), pp.94-105.

Gupta, Y. P. and Goyal, S. (1989), "Flexibility of Manufacturing Systems: Concepts and Measurements", *European Journal of Operational Research*, 43, pp.119-135.

Gupta, Y. P. and Goyal, S. (1992), "Flexibility Trade-offs in a Random Flexible Manufacturing System: A Simulation Study", *International Journal of Production Research*, 30, pp.527-557.

Gupta, Y. P. and Somers, T. M. (1992), "The Measurement of Manufacturing Flexibility", *European Journal of Operational Research*, 60, pp.166-182.

Gustavsson, S. O. (1984), "Flexibility and Productivity in Complex Production Processes", *International Journal of Production Research*, Vol. 22, No. 5, pp.801-808.

Hall, R. W. (1983), *Zero Inventories*, Dow Jones-Irwin, USA.

Hall, R. and Tonkin, L. (Eds.) (1990), *Manufacturing 21 Report: The Future of Japanese Manufacturing,* Association for Manufacturing Excellence, Wheeling, IL.

Hayes, R. H. and Wheelwright, S. C. (1984), *Restoring Our Competitive Edges--Competing Through Manufacturing,* Wiley, NK.

Hill, T. (1985) *Manufacturing Strategy*, MacMillan, London.

Hyun, J. H. and Ahn, B. H. (1992), "A Unifying Framework for Manufacturing Flexibility", *Manufacturing Review*, Vol. 5, No. 4, pp.251-260.

Jaikumar, R. (1986), "Postindustrial Manufacturing", *Harvard Business Review*, Vol. 64, pp.69-76.

Kickert, W. J. (1985), "The Magic Word Flexibility", *International Studies of Management and Organization*, Vol.14, No.4, pp.6-13.

Mandelbaum, M. (1978), "Flexibility in Decision Theory: An Exploration and Unification" unpublished Ph.D. dissertation, Department of Industrial Engineering, University of Toronto, Canada.

Mascarenhas, B. (1981), "Planning for Flexibility", *Long Range Planning*, 14, pp.78-82.

Miller, J. G. and Roth, A. V. (1987), "Manufacturing Strategies", Executive Summary of the 1987 North American Manufacturing Futures Survey, Boston, MA.

Monden, Y. (1993), *Toyota Production System - An Integrated Approach to Just-In-Time*, (2nd Eds.), Industrial Engineering and Management Press, Institute of Industrial Engineers, Norcross, Georgia.

Muramatsu, R., Ishii, K. and Takahashi, K. (1985), "Some Ways to Increase Flexibility in Manufacturing Systems", *International Journal of Production Research*, 23(4), pp.691-703.

Nagel, R. and Dove, R. (Eds.) (1991), *21st Century Manufacturing Enterprise Strategy*, Iacocca Institute, Lehigh University, Bethlehem, PA.

Ramasesh, R. V. and Jayakumar, M. D. (1991), "Measurement of Manufacturing

Flexibility: A Value Base Approach", *Journal of Operations Management*, Vol. 10, NO. 4, pp.446-468.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Skinner, W. (1985), *Manufacturing: The Formidable Competitive Weapon*, Riley Ipsilamti, MI.

Slack, N. (1989), "Focus on Flexibility", in Wild, R. (Ed.), *International Handbook of Production and Operations Management*, Cassell Educational Ltd, London, pp.50-73.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advance Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Suarez, F. F., Cusumano, M. A. and Fine, C. H. (1996), "An Empirical Study of Manufacturing Flexibility in Printed Circuit Board Assembly", *Operations Research*, Vol. 44, No. 1, January-February, pp. 223-240.

Swamidass, P. M. (1985), "Manufacturing Flexibility: Strategic Issues", Discussion Paper 305, Graduate School of Business, Indiana University, IN.

Swamidass, P. M. (1988), *Manufacturing Flexibility*, Monograph No. 2, Operations Management Association.

Swamidass, P.M. and Newell, W.T. (1987), "Manufacturing Strategy, Environmental Uncertainty and Performance: A Path Analytic Model", *Management Science*, Vol. 33, No. 4, pp.509-524.

Upton, D. M. (1994), "The Measurement of Manufacturing Flexibility", *California Management Review*, Winter, pp.72-89.

Upton, D. M. (1995), "What really makes factories flexible?", *Harvard Business review*, July-August, pp. 74-84.

Wharton, T. J. and White, E. M. (1988), "Flexibility and Automation: Patterns of Evolution", *Oper. Management Review*, 6, 3, and 4, (Spring and Summer), pp.1-8.

Zelenovic, D. M. (1982), "Flexibility--A Condition for Effective Production Systems", *International Journal of Production Research*, Vol. 20, No. 3, pp.319-337

Chapter 2

Literature Review

- A Measurement-Orientated Perspective

2.1 Introduction

It has been observed that plant managers recognize flexibility as an important factor for competitiveness (Cox, 1989 and Miller and Roth, 1987). Massive investments in Advanced Manufacturing Technologies (AMTs), such as Flexible Manufacturing Systems (FMS) and Computer Integrated Manufacturing (CIM), have been made in order to enhance manufacturing flexibility (Swamidass, 1988). However, empirical evidence has proved that not only did those investments not receive proper attention at the decision making stage (Lim, 1987), but they also lacked adequate recognition and management at the implementation stage (Jaikumar, 1986).

The reason could be that plant managers seemed to rely on a technology level rather than a system level view, as Slack's (1987) observed, showing only a partial recognition of manufacturing flexibility. Swamidass (1988) also suggested that relying on machine level flexibility only could be inadequate to capture the advantage of flexibility without proper management of the system; moreover, distinguishing manufacturing flexibility into types and exploring their relationships would make for a better understanding of manufacturing flexibility. In all, it appeared that in practice managers did not understand manufacturing flexibility very well (Gupta and Somers, 1992).

In the academic area, there is a strong need to promote better understanding, and to develop models and methods for flexibility measures. Otherwise, it could be difficult to improve flexibility in operations management. As a result, considerable effort has been taken by researchers to make a clear perception of manufacturing flexibility in manufacturing systems, however, no unified consensus of manufacturing flexibility has appeared in the literature, especially in proposing measurement models at the operational level. Many methods have been proposed with different considerations and from different points of view and, hence, these have suggested different approaches to the measurements.

The main streams in the research field of manufacturing flexibility could be divided into three groups: strategy groups, tactical groups and operational groups (Hyun and Ahn, 1992).

(1) Strategic flexibility framework and/or reviewing the Literature

Strategy groups considered flexibility as a strategy variable and majored on its influence on market competitiveness. In order to consider an effective way of coping with uncertainties arising from internal and external environments, this group has classified manufacturing flexibility into several types, sometimes noted as flexibility indicators or flexibility dimensions.

This category includes reports which propose the integration of the perceptions on the conceptual framework of manufacturing flexibility and its clarifications. The reason is that it shows a variety and complexity of flexibility concepts to express flexibility indicators. Definitions of each flexibility type and measurement methods have been proposed by researchers from different viewpoints. These indicators were characterized by different content with the same item or having the same meaning in different notations.

By synthesizing the concept of flexibility of the manufacturing systems proposed in the literature, Sethi and Sethi (1990) developed an integrated framework and exhibited 11 measurement indicators which included not only its meaning and purpose but also its method of measurement. In addition to Browne et al.'s (1984) eight types of flexibility, Sethi and Sethi (1990) added material handling flexibility, programme flexibility and marketing flexibility to the classifications. Moreover, Gupta and Somers (1992) took those 11 indicators to design a questionnaire which included 34 measuring items, sent it to 269 companies, and from factor analysis, they reduced them to 9 indicators including 21 items.

The work in this group is focused on proposing an integrated framework with classifying different flexibility types, defining each type of flexibility and suggesting the corresponding measurement approach. Researchers who fall into this group include Browne et al. (1984), Sethi and Sethi (1990), Suarez et al. (1991), Gupta and Goyal (1992), Gupta and Somers (1992), Hyun and Ahn (1992) and Upton (1994). Those reports also referred to how to measure the proposed types of flexibility, however, they tended to propose qualitative suggestions (Sarker et al. 1994).

The problem in this category is that they do not seem to define the boundary of the system in which the flexibility type has been indicated. Therefore, some researches proposed partial types of flexibility within the manufacturing systems, while some others included factors outside the domain of a manufacturing system. Another problem could be that the definitions of types of flexibility might overlap each other to some degree. Unnecessary difficulties and confusion could arise in applying the definition to the operational activities and measures.

(2) Flexibility and performance

Tactical groups are concerned with manufacturing performances which were influenced by flexibility. The focus in this group is engaged in finding the relationships between flexibility and those performance indicators. The measurement approaches applied in this category first of all require the definition of the types of flexibility for the investigation, and then propose the corresponding measurement approaches.

Zelenovic (1982) examined the relationship between flexibility and productivity and concluded that increased flexibility should decrease productivity of the system. Chen and Chung's (1991) contrary finding is that the improvement of volume flexibility could lead to increased system productivity.

In Gupta and Goyal's (1992) application, the chosen parameters include machine idle time and job waiting time as the performance indicators to examine the trade-offs between different types of flexibility in Browne et al.'s (1984) classification. Some other performance parameters were obviously applicable to the measurement, for example, throughput, make span, work-in-progress, equipment utilization, and the time job spend in the queue (Law, 1988).

Benjaafar and Ramakrishnan (1996) suggested a performance-based approach for quantifying the value of flexibility. The flexibility type examined was sequencing flexibility, which was defined as the possibility of interchanging the manufacturing operations' order. The performance criteria included production lead time, work-in-progress and part waiting time.

Chen and Chung (1996) adopted the approach of Brill and Mandelbaum (1989) to measure machine flexibility and proposed a ratio of actual routes to the potential routes for a part type set to measure routing flexibility. The aim in their work is to investigate the relationship between these two types of flexibility and the performance of the system in terms of job span and system utilization.

Suarez et al. (1996) investigated the factors in terms of technology and non-technology, such as human resources, suppliers and wage schemes, that affected manufacturing flexibility at 31 printed circuit-board plants in Europe, Japan, and the United States. They found that more automated plants tend to be less flexible, and flexibilities could be improved by high involvement of labour in problem-solving activities, good relationship with suppliers, and flexible wage schemes.

Generally, the approaches adopted in this category were based on either the models developed in the next category or the methods extended from the definitions in the previous category. In order to construct a feasible operational environment, the measurement methods proposed in this category tended to be oversimplified. As the application approaches did not seem to consider the factors thoroughly, confusion and contradictions also appeared in the conclusions.

(3) Flexibility and measurement

Operational groups concentrated their efforts on proposing methods of measurement for each classified type of manufacturing flexibility. They thought that if the measurement approach for each flexibility type could not be measured properly, it would not be possible to check if the effort had been made in the right direction to manage or improve it.

The work in this category is an empirical quantitative study that had concrete data, rigorous definition, and was stated clearly in operations. Despite many attempts which have been made to develop a single measure for any type of flexibility, the extension from conceptual model to actual quantitative measurement is still a long way off. Up to now, the proposition of quantitative indicators is still measured in part not overall and from all sides. Therefore, Bateman et al., (1999) stated that it is not thought possible to propose unified measurement framework for the universal flexibility types. However, this thesis argues with this statement in the following Chapters.

The quantitative factors adopted in this category related mostly to the three dimensions of cost, time and range, suggested by Slack (1983) and Gerwin (1987, 1993). Son and Park (1987) applied the cost dimension to the measurement of four types of flexibility, namely equipment flexibility, product flexibility, process flexibility and demand flexibility. Barad and Sipper (1988) quoted in Petri-Nets model to the measurement of manufacturing flexibility is time dimension approach. Kumar (1986, 1987), Yao (1985), Gupta et al. (1989) and Yao and Pei (1990) cited information theory and Mandelbaum and Buzzacott (1986), and Mandelbaum and Brill (1990) adopted decision theory as the method in measuring flexibility in relation to range consideration.

Barad and Sipper (1990) included time and range as the measurement factors in their application. They all seem to lack the consideration of integration. Some recent researches, such as Das (1996) and Chung and Chen (1996), basically adopt previous approaches (Browne et al., 1984, Chatterjee et al., 1984 and Brill and Mandelbaum, 1989) for doing their empirical tests. Barad and Nof (1997) suggested time (and sometimes included cost) and range to the measurement in their report.

The approaches developed in this category for the measurements are generally theoretical based orientation. The main question in this category is that some of the approaches seem difficult to apply to industry, and others are somewhat native and arbitrary. Some researchers have argued that the models at the operational level were too abstract or become too complicated and untraceable when the systems are increasingly larger and are hence difficult to apply in practice. As flexibility in manufacturing systems embodies multi-dimensional attributes and is very complicated in its concept, the real data are hard to gather from field studies. This might be the reason that the empirical applications of manufacturing flexibility to the factory are unlikely to be easy as some of performance criteria, such as quality or productivity. This could lead to difficulty in understanding and, of course, in applications.

It seems necessary to develop measurement models that are empirically sensible and easily applicable for managers. A tool, like computer software, should be developed because the flexibility concept perceptively incorporates complexity, muli-dimensions and muti-attributes in its characteristics, and the computations seem inevitably to be complicated.

It is not the intention of this research to explore the entire aspects related to manufacturing flexibility discussed in the literature, but rather to focus on the measurement-orientated viewpoint in order to examine and propose a framework for the measurement of manufacturing flexibility. Three major aspects, namely flexibility types, measurement factors and measurement domain should be considered when focusing on the measurement of manufacturing system flexibility. Therefore, this research will mainly concentrate on the area related to the measurement approaches and quantifiable factors.

2.1.1 A classification scheme of manufacturing flexibility in the literature

Much research has been done on the classification of manufacturing flexibility into types, dimensions, needs, measurement approaches, decision levels, and system levels. These include Mandelbaum (1978), Buzacott (1982), Zelenovic (1982), Browne et al. (1984), Gerwin (1982, 1987, 1993), Slack (1983, 1989), Jaikumar (1984), Gustavsson (1984), Carter (1986), Frazelle (1986), Yamashina et al. (1986), Azzone and Bertele (1987), Son and Park (1987), Taymaz (1989), Sethi and Sethi (1990), Hyun and Ahn (1992), Gupta and Somer (1992), Chen et al. (1992), Gerwin (1993), Gupta (1993), Barad and Nof (1997), among others.

This thesis is mainly concerned with how to measure manufacturing flexibility properly and precisely. Measurement factors, approaches, methods and models for the assessment of manufacturing flexibility either with different types or some area related to different system levels, is the major task in this research. This Chapter is organized to discuss the researches which have been reported in the literature, directly related to the area of operational measurements of manufacturing flexibility. Figure 2.1 proposes four streams of research in the literature, which include: (1) flexibility typologies, (2) flexibility measurement approaches, (3) flexibility dimensions, (4) flexibility needs. The framework illustrated in Figure 2.1 might provide a clearer picture of the research in the area of operational measurement of manufacturing flexibility in the literature. Following this framework, an extended scheme of operational measurement research will be proposed in Section 2.6.

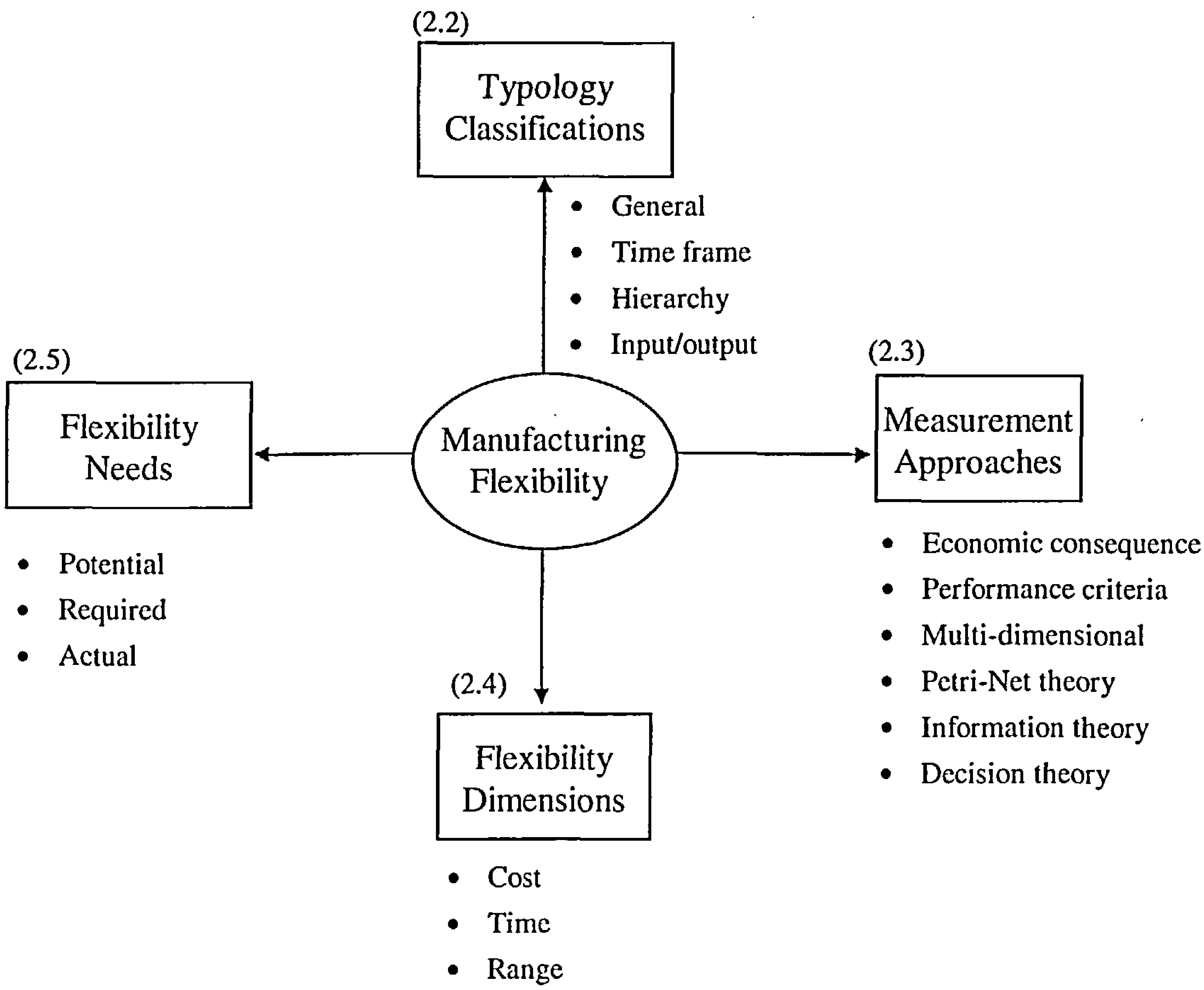


Figure 2.1: A classification framework to manufacturing flexibility research

In this Chapter, the main focus is to investigate the detailed typologies of flexibility, including their definitions, the area related to the factors of measurement dimensions, approaches and methods. Section 2.2 classifies manufacturing flexibility into types, defines each type of flexibility, and then groups them into three time spans, and a hierarchical structure. Section 2.3 identifies the measurement approaches in the literature. Section 2.4 focuses on a summarization with the three dimensional approach, range, time and cost, for each type of flexibility as basic factors for flexibility measurements. Section 2.5 develops the need for the improvement of each type of flexibility. Section 2.6 proposes an extension of the classification scheme of current research. Flexibility attributes and flexibility measurement at different system levels are two additional streams to the classification scheme. These two streams could be worthwhile for future research in this subject. Section 2.7 illustrates ten types of attributes relevant to the measurement models of manufacturing flexibility; while, Section 2.8 demonstrates a hierarchical structure of a flexible system with a consideration of the flexibility attributes.

2.2 Typology classifications

There has been a consensus among researchers to classify manufacturing flexibility into types, in order to understand it more precisely, because different types of manufacturing flexibility can be obtained and improved by different means and, in addition, they can be used to cope with different conditions and types of disturbances (Correa, 1994).

Slack (1989) stated that managers should have an idea of what types of flexibility are important to their system; otherwise, they will fail to focus their efforts on the most competitive directions. The classification of manufacturing flexibility into types is useful to the understanding of flexibility itself. Also, it will be helpful in finding ways to improve flexibility in a manufacturing system.

Sethi and Sethi's (1990) report will be adopted in the present research as the basis to compare the others' studies, illustrated in Table 2.1. However, as described in Chapter 1, market flexibility has been excluded in this research, and instead this research considers that labour flexibility should be included.

Marketing flexibility has been considered outside the domain of a manufacturing system, as it is parallel to manufacturing flexibility from a corporation's functional viewpoint. Moreover, marketing flexibility could be embodied in the concept of product flexibility, production flexibility, volume flexibility and expansion flexibility. It would therefore be unnecessary to measure marketing flexibility. Labour flexibility is vitally important to contribute a system flexible, and many researchers, including Gerwin (1987), Cox (1989), Chen et al. (1992), and Hyun and Ahn (1992), have sustained this viewpoint. Suarez et al.'s (1996) empirical investigation also gave supportive evidence. Therefore, there are still 11 types of flexibility illustrated as the basis for the comparison. Gupta and Goyal (1989) adopted Browne et al.'s (1984) definition to classify the previous researches into 8 types of flexibility. Table 2.1 could be thought as an extension of Gupta and Goyal (1989). The cell, which has been marked with [✓], represents the same terminology used.

Table 2.1: A classification of manufacturing flexibility in the literature based on Sethi and Sethi's (1990) definition

Authors \ Flexibility types	Machine flexibility	Material handling flexibility	Labour flexibility	Process flexibility	Routing flexibility	Programme flexibility	Operation flexibility	Product flexibility	Volume flexibility	Production flexibility	Expansion flexibility
Mandelbaum (1978)				Action						State	
Buzacott (1982)	✓			Job							
Gerwin (1982)				Design	✓			Parts	✓	Mix	
Zelenovic (1982)				Adaptation						Application	
Slack (1983)								New Product	✓	Product mix	
Browne et al. (1984)	✓			✓	✓		Process sequence	✓	✓	✓	✓
Chatterjee et al. (184)				Part specific	✓			Part mix			
Gustavsson (1984)	✓							✓	Demand		Machine
Jaikumar (1984)	✓	✓			✓	✓		✓			
Carter (1986)	✓			Mix	✓			Mix change		✓	✓
Frazelle (1986)				Design	✓			Parts	✓	Mix	
Yamashina et al. (1986)								Short product life	✓	Variant	
Azzone and Bertele (1987)				✓	✓			Produce	✓	✓	
Son and Park (1987)	Process							Equipment	Demand	Product	
Barad and Sipper (1988)	Machine setup	Transfer		✓	✓		Operations		✓		
Slack (1989)			✓	✓				✓	✓	Mix	
Chen et al. (1992)	✓	✓	✓	✓	✓	Programm-ing		✓	✓	Mix	✓
Gupta and Somers (1992)	✓	✓		✓	✓	Programm-ing		Product & Production	✓		Expansion & Market
Hyun and Ahn (1992)	✓		Worker	✓	✓	✓	Control	✓	✓	Mix	✓
Gerwin (1993)					✓			Changeover and Modification	✓	Mix	

The following description chronologically summarizes the research, classified by authors, in order to provide a clearer picture of the evolution in this area. The definitions refer to Table 2.2. Mandelbaum (1978) proposed two types of flexibility, namely action flexibility and static flexibility. The former proceeds on the dynamic perspective in a situation where the future is unknown, while the later copes with rather static situations so that the system is able to operate well in many different circumstances.

Buzacott (1982) characterized two types of flexibility, namely job flexibility and machine flexibility. Job flexibility refers to the ability of a system to cope with the changes caused by factors outside the system, meaning external changes, such as product changes, order volume changes, product-mix changes, etc. Machine flexibility is the ability of the system to cope with internal changes, e.g., machine breakdowns, tool breaks, labour absenteeism, etc.

Gerwin (1982) considered that a flexible system should have the ability to process a mix of parts, to add or remove parts from the product mix, to reroute a given part of production, to accommodate engineering changes for the parts, to change in volume and to control the variation in processed items. Therefore Gerwin proposed five types of flexibility in terms of mix flexibility, parts flexibility, routing flexibility, design change flexibility, volume flexibility and material flexibility respectively.

Zelenovic (1982) suggested two types of flexibility, namely application flexibility and adaptation flexibility. Application flexibility is related to the ability to meet design adequacy, the probability that the system can adapt itself to environmental conditions and requirements with the given structure design parameters. Gupta and Goyal (1989) stated that it would be quite difficult to find this probability. So, they proposed that the degree of utilization is the concept most related to this flexibility. Adaptation flexibility is related to the time needed for the system to adapt itself to the change of jobs.

Slack (1983) proposed five types of flexibility, namely new product flexibility, quality flexibility, volume flexibility, delivery flexibility and product mix flexibility. Slack's (1983) classification seems to consider the wider domain of manufacturing flexibility. Quality flexibility and delivery flexibility were also suggested. Quality flexibility could be related to the process flexibility of Sethi and Sethi's (1990) classification; while delivery flexibility seems to be excluded from Table 2.2.

Browne et al.'s (1984) summation seemed to be more accepted and adopted in many researches. They proposed eight types of flexibility, which have been used as the basic typology by Gupta and Goyal (1989) to summarize previous reports. There are machine flexibility, process flexibility, product flexibility, routing flexibility, volume flexibility, expansion flexibility, process sequence flexibility and production flexibility. Although their work seemed comprehensive enough in the classification of types, it lacks some other considerations, such as material handling system, labour and programme flexibility.

Gustavsson (1984) demonstrated three types of flexibility, namely machine flexibility, product flexibility and demand flexibility, which were related to quantitative considerations. Machine flexibility was characterized as the ability to cope with project changes in the forms of machines, production method, systems and personnel, in the system. The ratio of residual value of investment for the next product model was proposed as the measurement of machine flexibility. Product flexibility was defined in the same way as by other authors and proposed the ratio of residual value of the old model to the new model of the product as the measurement method. Demand flexibility was defined as the possibility of demand fluctuation over a period of time.

Jaikumar (1984) introduced three types of flexibility, namely product flexibility, programme flexibility and process flexibility. Product flexibility related to the incremental costs of introducing a new part or product. Programme flexibility was first suggested by Jaikumar (1984). It related to the ability to run a system relying entirely on computers. Process flexibility is defined as a rather broad concept as the ability of a system to produce parts through multiple alternative paths in order to increase the utilization of the system. Jaikumar further broke drown process flexibility into three types of flexibility, namely machine flexibility, material handling system flexibility and pallet fixture flexibility. The ability to maintain the required tooling for an operation at several machines was used to characterize machine flexibility. Material handling system flexibility, defined by Jaikumar appeared to be related to what other authors have called routing flexibility. Pallet fixture flexibility seems to be considered too detailed a classification for other researchers.

Carter (1986) defined six types of flexibility, including machine flexibility, process flexibility, product flexibility, routing flexibility, expansion flexibility and production flexibility. Carter's (1986) definition, although qualitatively orientated and mostly consistent with Browne et al. (1984), seemed to be more detailed, and specified measurement considerations in terms of a set of tasks, the range of dimensions and the cost and time for the changeovers.

Frazelle's (1986) classification also had a qualitative orientation. He described five types of flexibility - process flexibility, product flexibility, volume flexibility, production flexibility and design change flexibility. Design change flexibility seems different from the others, however, it was classified in process flexibility by Gupta and Goyal (1989). The other types of flexibility proposed in Frazelle (1986) were similar to the previous authors'.

Yamashina et al. (1986) suggested three type of flexibility, namely variant flexibility, volume flexibility and short product life flexibility. Variant flexibility is the same as production flexibility, while short product life flexibility is the same as product flexibility. It appears that different terms were used to define the same meaning.

Azzone and Bertele (1987) synthesized the work of Buzacott (1982), Gerwin (1982) and Browne et al.'s (1984), and proposed six types of flexibility in terms of routing, process, produce, volume, expansion and production, and further suggested qualitative measurement methods respectively.

Son and Park (1987) proposed the flexibility measurement similar to the methodology of measuring productivity. Four types of flexibility, namely equipment flexibility, product flexibility, process flexibility and demand flexibility were illustrated by numerical models. They suggested the ratios of total output divided by idle cost of equipment, setup cost, waiting cost of part processed and inventory costs of finished products and raw materials as the measurement of those four types of flexibility respectively.

Barad and Sipper (1988) defined six type of flexibility: machine setup flexibility, process flexibility, transfer flexibility, routing flexibility, volume flexibility and operation flexibility. Barad and Sipper's (1988) report was mainly based on Browne et al. (1984), but added two types of flexibility, namely transfer flexibility and operation flexibility. The former is the same as material handling system flexibility; while, the latter, although they used the same notation as Kumar (1986), had a different meaning, as the ability to interchange the sequence of operations on each part, denoted as operation flexibility.

Slack (1989) described two levels of flexibility types, namely system flexibility types and resource flexibility types. The former includes product flexibility, mix flexibility, volume flexibility and delivery flexibility. While the later includes process flexibility, labour flexibility, supply system flexibility and control system flexibility. At the resource level, the former two types of flexibility are characterized as structure flexibility, while the later two types are infrastructure flexibility. The reason for Slack's (1989) classification is that the system flexibility directly contributes to the competitiveness of the firm, while resource flexibility contributed to system flexibility.

Chen et al. (1992) classified ten types of flexibility into two categories, namely manufacturing-orientated flexibility, including machine flexibility, labour flexibility, material handling flexibility, routing flexibility, process flexibility and programme flexibility; and market-orientated flexibility, including product flexibility, volume flexibility, product-mix flexibility and expansion flexibility. Their classification states that market-orientated flexibility is supported by manufacturing flexibility. Suarez et al. (1996) suggested a similar point of view that there are two groups of flexibility. One is defined as the basic or first order flexibility types, which is directly related to their customers, the same as market-orientated flexibility, including mix flexibility, volume flexibility, new-product flexibility and delivery-time flexibility; while the others are the lower-order flexibility types, including routing flexibility, system flexibility, component flexibility, etc.

Gerwin's (1993) classification seemed slightly different from the others. He proposed six types of flexibility namely, mix flexibility, changeover flexibility, modification flexibility, volume flexibility, rerouting flexibility and material flexibility. The proposal of those six types of flexibility is relevant to the uncertainty factors caused by the environment. Mix flexibility represents the ability of a system to handle a range of products or variants. Changeover flexibility and modification flexibility are both related to the ability to introduce new products; however, the former concerns entirely new products, while the latter concerns only a minor change to the current products. Volume and rerouting flexibility are similar to those defined by other researches. Material flexibility is defined as the ability to cope with unexpected variations from the input side. This type of flexibility is different from other reports, as there is no such type of flexibility in the literature.

2.2.1 Typologies and their definitions

On the purpose of proposing a framework for the measurement of manufacturing flexibility in this research, it is necessary to look into a detailed classification of flexibility types in manufacturing with a clear and appropriate definition of each different type of flexibility. The approaches or the measurement models for evaluating each type of manufacturing flexibility should be based on a clear perception of the meaning of the evaluated objectives and should give them proper definitions.

Following those precise definitions, it is therefore possible to lead to propose the proper approaches, methods and models for the measurement of manufacturing flexibility. Table 2.2 also adopts Sethi and Sethi's (1990) classification and is consistent with Table 2.1, which suggested 11 types of measuring manufacturing flexibility of the systems.

Table 2.2: Summarized definitions of 11 proposed types of flexibility

Flexibility type	Definition
1.Machine Flexibility	1. Buzacott (1982): the ability of the system to cope with changes and disturbances at the machines and workstations. (internal change) 2. Browne et al. (1984): the ability to replace worn out or broken tools, change tools in a tool magazine, and assemble or mount the required fixtures, without interference or long setup times. 3. Gustavsson (1984): the ability to cope with project changes in terms of machines, production method, systems and personnel, in the system. 4. Carter (1986): the ability of a system to perform a variety of processing or assembly operations. 5. Son and Park (1987)-Process flexibility: the adaptability of the system to various changes in part processing, such as equipment and tool breakdowns. 6. Barad and Sippler (1988): the ease of making the change required to produce a given set of part types. 7. Brill and Manbelbaum (1989): the weighted effectiveness of a machine or a group of machines to perform a given set of parts relative to a reference task set. 8. Sethi and Sethi (1990): refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another. 9. Chen et al. (1992): the capability of a machine to perform different operations required by a given set of part types. 10. Hyun and Ahn (1992): the ability to replace worn out or broken tools, change tools in a tool magazine, and assemble or mount the required fixture, while interference or long time, and the capability to process wider range of products.
2.Labour Flexibility	1. Chen et al. (1992): the ability of the workforce to perform a broad range of manufacturing tasks effectively. 2. Hyun and Ahn (1992): the ability of line workers to operate various types of machines, to alter working methods and standards.
3.Material Handling Flexibility	1. Barad and Sippler (1988)-Transfer flexibility: the system's capability to move parts between machining centers. 2. Sethi and Sethi (1990): the ability to move different part types efficiently for proper positioning and processing through the manufacturing facilities it serves. 3. Chen et al. (1992): the capability to transport different parts form the loading area , through machining centres, to the unloading or storage area.
4.Operation Flexibility	1. Browne et al. (1984)-Process Sequence Flexibility: the ability to interchange the ordering of several operations for each type. 2. Barad and Sippler (1988): the ability to interchange the ordering of several operations on each part, while complying with the design restrictions. 3. Sethi and Sethi (1990): the ability to produce a part in different ways. 4. Benjaafar and Ramakrishnan (1996) - Sequencing flexibility: the possibility of interchanging the order in which required manufacturing operations are performed.

Flexibility type	Definition
5.Process Flexibility	1.Mandelbaum (1978)-Action flexibility: related to situations where decisions are made sequentially, without knowledge of the future. 2. Buzacott (1982)-Job flexibility: the ability of the system to cope with changes in the jobs to be processed by the system.(external change) 3. Gerwin (1982)-Design change flexibility: the ability of the system to quickly implement engineering design changes for a particular part. 4. Zelenovic (1982)-Adaptation flexibility: the amount of time needed for the system to adapt to a change in the job task. 5. Browne et al. (1984): the ability to vary the steps necessary to complete a task. 6. Jaikumar (1984): the ability of a system to produce parts through multiple alternative paths in order to increase the utilization of the system. 7. Carter (1986): the ability of the system to produce simultaneously or periodically, multiple products in a steady operating mode. 8. Frazelle(1986)-Design change flexibility: permits the rapid and inexpensive implementation of engineering design changes for a particular part. 9. Azzone and Bertele (1987): the ability of the system to operate products changes among a given set of part types. 10. Barad and Sippler (1988): the system process variety. 11. Sethi and Sethi (1990): related to the set of part types that the system can produce without major setups. 12. Chen et al. (1992): the capability of a system to produce a given set of parts.
6.Routing Flexibility	1. Gerwin(1982): the ability of the system to reroute a given part if the machine used in its manufacturing is incapacitated. 2. Browne et al. (1984): the ability to vary machine visitation sequences (for example, in the case of breakdowns) and to continue producing the given set of part types. 3. Carter (1986): the ability of the system to perform operations on alternate machine, in alternate sequences, or with alternate resources. 4. Frazelle (1986): the ability of the system to dynamically assign parts to the machines quickly and economically. 5. Azzone and Bertele (1987): the ability of the system to operate with one or more machines not working. 6. Barad and Sippler (1988): specified as product mix dependent, while retaining its classical definition. 7. Sethi and Sethi (1990): Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system. 8. Chen et al. (1992): the capability to process a given set of part types using more than one route. 9. Hyun and Ahn (1992): the ability to vary machine visiting sequence to produce a set of part types.
7.Programme Flexibility	1. Jaikumar (1984): the ability to run virtually untended during the second and third shift. 2. Sethi and Sethi (1990): the ability of the system to run virtually untended for a long period. 3. Chen et al. (1992)-Programming flexibility: The capability of a production system to operate untended for a certain period of time. 4. Hyun and Ahn (1992): The ability to handle various contingencies during operations such as machine breakdowns, quality problems, input material associated problems, and so forth.

Flexibility type	Definition
8.Production Flexibility	1. Gerwin (1982)-Mix flexibility: the ability of the system to simultaneously process a mix of different parts that are loosely related to one another. 2. Zelenovic (1982)-Application flexibility: the value of "design adequacy" the probability that the given structure of a system will adapt itself to environmental conditions and to the requirements, within the limits of the given design parameters. 3. Slack (1983)-Product mix flexibility: the ability of the system to manufacture, not necessarily simultaneously, a particular mix of products within the minimum planning period used by the company. 4. Browne et al. (1984): the ability to quickly and economically vary the part variety for any product that an FMS can produce. 5. Carter (1986): the ability of a system to produce a range of products without the need for adding capital equipment. 6. Frazelle (1986)-Product mix flexibility: requires the simultaneous processing of a mix of different parts loosely related to one another by shape or routing. 7. Azzone and Bertele (1987): the size of the set of parts that the manufacturing system can produce. 8. Mandelbaum (1978)-State flexibility: related to situations where a given system is able to operate well in many different circumstances. 9. Son and Park (1987)-Product Flexibility: the adaptability of a manufacturing system to change in product mix. 10. Sethi and Sethi (1990): the universe of part types that the system can produce without adding major capital equipment. 11. Chen et al. (1992): the capability of a production system to respond to different product mix changes in the market. 12. Hyun and Ahn (1992): the adaptability of a manufacturing system to changes in product mix.
9.Volume Flexibility	1. Gerwin (1982): the ability of a system to accommodate shifts in volume for a given part. 2. Slack (1983): the ability of the system to change output volume. 3. Browne et al. (1984): the ability to operate an FMS profitably at different production volumes. 4. Gustavsson (1984)-Demand flexibility: related to the possibility of demand fluctuation over a period. 5. Frazelle (1986): allows the accommodation of shifts in volume for a given part. 6. Azzone and Bertele (1987): the ability of a system to operate with a low reduction in the operating margin caused by a decrease in demand. 7. Son and Park (1987)-Demand flexibility: the adaptability to change in demand. 8. Barad and Sippler (1988): referred to as system setup flexibility. 9. Sethi and Sethi (1990): Volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels. 10. Chen et al. (1992): the capability of a production system to operate, in the short term, at different various batch sizes and/or at different production volumes economically. 11. Hyun and Ahn (1992): the ability to accelerate production very quickly and juggle the orders to meet demands for unusually rapid delivery, and to operate profitably at different production volumes.

Flexibility type	Definition
10.Product Flexibility	1. Gerwin(1982)-Parts flexibility: the ability of the system to handle the addition to, or the removal of, parts from the mix over time. 2. Slack (1983)-New product flexibility: the ability of the system to make something novel. 3. Browne et al. (1984): the ability to change over to produce a new product, within the defined parts spectrum, economically and quickly. 4. Gustavsson(1984): related to the possible changes in the products. 5. Carter (1986): Mix-change flexibility: the ability of the system to change the product mix inexpensively and rapidly. 6. Frazelle (1986)-Parts manufacturing flexibility: requires that changes in product mix, volume, routing, and design be absorbed quickly and economically. 7. Azzone and Bertele(1987)-Produce flexibility: the ability of the system to produce new products with minimal cost. 8. Son and Park (1987)-Equipment flexibility: the capability of the equipment to accommodated new products and some variants of existing products. 9. Sethi and Sethi (1990): the ease with which new parts can be added or substituted for existing parts. 10. Chen et al. (1992): the ability to changeover to introduce new products and respond to customers' requests. 11. Hyun and Ahn (1992): the ability to handle difficult, nonstandard orders and to take the lead in new product introduction.
11.Expansion Flexibility	1. Browne et al. (1984): the capability of building a system and expanding it as needed, easily and modularly. 2. Gustavsson (1984)-Machine flexibility: related to projected changes in the production system. 3. Carter (1986): the ability of the system to handle an increase in capacity or a change in the product range. 4. Azzone and Bertele (1987): the number of product mixes the system can produce by adding new machines. 5. Sethi and Sethi (1990): Expansion flexibility of a manufacturing system is the ease with which its capacity and capability can be increased when needed. 6. Chen et al. (1992): the capability of an existing system to expand its facilities to cope with long term increase in demand. 7. Hyun and Ahn (1992): the ability of the system to handle an increase in capacity or a change in the product range.

Although many studies have appeared in the literature, there is no unified classification of a framework to characterize the types of flexibility. Confusion has arisen in the literature, such as different notations being used to present the same type of flexibility, or the same notation of flexibility types being used to denote different meanings, and overlaps have appeared in defining different types of flexibility Swamidass (1988).

2.2.2 Time scale classification

The flexibility of a system has been generally defined as its ability to adapt to changing circumstances. Since changes occur in different time spans, it is imperative for a system to have different kinds of abilities to cope with those changes encountered in the environment, internally and externally.

In Chapter 1, it has been mentioned that each type of flexibility is related to a different kind of environmental change. It is therefore sensible to classify flexibility types with different time scales, namely, short term, medium term and long term. Such a consideration is related to decision making, in that if managers want to pursue or improve system flexibility they should know which flexibility types could be achieved in the short term, medium term or long term.

Gustavsson (1984) may have been the first to propose the application of time scale to manufacturing flexibility. Carter (1986) stated that "different types of flexibility impact production in different time frames", and divided the time frames into four categories, namely very short-term, short-term, medium-term, and long-term, typically corresponding to one to three days, one to two months, six months to two years and five or more years respectively.

Yilmaz and Davis (1987) characterized flexibility types with different time dimensions, namely 'flexibility at times', needed to cope with unpredictable interruptions, 'flexibility after a time', needed to handle foreseeable, short term changes, and 'flexibility over time', needed to handle known, long term changes. Machine flexibility and routing flexibility belong to the first time span; product, process and process sequence flexibilities pertain to the second time span; while volume, expansion and production flexibilities are related to the last time span.

Carlsson (1992) also identified three aspects of flexibility in terms of operational flexibility, tactical flexibility and strategic flexibility. These three aspects of flexibility are actually related to the three time scales, namely short-term, medium-term and long-term respectively. In the short term, only operational sequencing and scheduling can be varied. Medium-term flexibility is the ability related to the changes in production rate or production mix and some moderate design changes in products. Finally, long-term flexibility is concerned with the ability of a system to introduce new products to the market or the re-positioning of its market segments. More specifically and slightly changed by Upton (1994), operational flexibility involved daily changes, tactical flexibility related to quarterly changes, while strategic flexibility concerned yearly changes.

2.2.2.1 Short-term flexibility

Short-term flexibility is concerned with operational decisions and is related to shift to shift or day to day works, e.g., operation sequence, production schedules and so forth. A system is short-term flexible if the system is able to change its operation sequence and production schedules so as to cope with breakdowns of vital machinery or a sudden shortage of raw materials or parts. Routing flexibility, operation flexibility and programme flexibility are related to this area.

2.2.2.2 Medium-term flexibility

Carlsson (1989) stated that the medium-term flexibility was decided when the system was built. It relates to the choice of production technologies. The changes in such division include production rate, production-mix and minor product design changes. The ability of the system is needed to operate at varying rate, handle a variety of parts, accept different parts at random sequence, accommodate minor design changes and so forth. Flexibility types fall in this division are process flexibility, volume flexibility, product-mix flexibility, machine flexibility, material handling flexibility and labour flexibility.

2.2.2.3 Long-term flexibility

Long-term flexibility concerns the ability of a firm to re-position itself in its competitive environment. In the long-term perspective, changes could arise from product demands, consumer preferences, the number of competitors and technology innovations that will lead to a wide variants in the external environment. Managers therefore need to point out which market segments will be engaged, what basic design changes will be made to its processes, what kind of facilities, manpower and technologies should be employed in the system and where production sites will be located. Flexibility types related to such a time span include process flexibility, product flexibility and expansion flexibility.

Taymaz's (1989) report concluded that there existed a need to explore the relationship between different terms of flexibilities. Chandra and Tombak (1992) also suggested in their conclusion that it is necessary to explore the relationships between different types of flexibility. Work on such aspects should be based on the development of the hierarchical structure of the flexibility types.

2.2.3 Hierarchical classification

The purpose of classifying flexibility types into a hierarchical structure is to understand the relationships between the types of manufacturing flexibility. As researchers have mentioned that different types of flexibility could involve trade-offs, improving certain types of flexibility made it necessary to consider the effects on the other types of flexibility, or to consider which types of flexibility could be the basis of the power for the enhancement. Slack's (1989) classification, which has been illustrated in Section 2.2, is also in the form of a hierarchical structure.

Taymaz (1989) classified flexibility types as a hierarchical structure with three levels, namely component level, operation level and system level. At the basic component level, there are three types: machine flexibility, routing flexibility and control flexibility. With the interconnection and integration of these components, Taymaz identified the operations level of flexibility types as volume flexibility, mix flexibility, process flexibility, product flexibility and expansion flexibility. Finally, the last and most abstract system level is production flexibility.

Sethi and Sethi (1990) suggested a linkage scheme for the various flexibilities reviewed in their report. The scheme divided those flexibilities into three levels. The component or basic level contains machine flexibility, material flexibility and operation flexibility. The second level of flexibilities are process flexibility, routing flexibility, product flexibility, volume flexibility and expansion flexibility. The third level of flexibilities are characterized as aggregate flexibilities, including programme flexibility, production flexibility and Market flexibility.

Hyun and Ahn (1992) distinguished flexibility types into three different viewpoints: namely the system view, the environmental-associated view and the decision-hierarchy view. The system view of manufacturing flexibility presents a system-component relationship that closely corresponds to the manufacturing structure of the firm. In this category, there are machine flexibility, routing flexibility, control flexibility and worker flexibility. Machine flexibility and routing flexibility are characterized as hardware orientated, built *a priori* components in the system; while control flexibility and worker flexibility are software orientated. The authors also stated that software orientated flexibility types could be more important than those of hardware orientated flexibility types.

The environmental-associated view of manufacturing flexibility includes expansion flexibility, product flexibility, mix flexibility, volume flexibility and programme flexibility. The authors viewed this category as more related to the traditional perception of manufacturing flexibility, the ability of the system to cope with internal and external uncertainties in the environment. These flexibility components are mostly static in the sense that they are embodied in process technology. The authors observed that dynamic flexibility, which is characterized by the organizational culture in the forms of learning and the knowledge intensity of the system, has been the focus of Japanese companies to enhance their competitiveness.

The decision-hierarchical view is related to the perception of three levels of system decision-making in terms of operational flexibility, tactical flexibility and strategic flexibility and they are correspondingly related to the time scale classification: namely short-term flexibility, mid-term flexibility and long-term flexibility, stated above. The authors considered that static and dynamic programme flexibility falls in the basic level of the category. Volume flexibility falls into the dynamic aspect, and volume flexibility, process flexibility and product flexibility fall in the static aspect belonging to tactical flexibility. Static expansion flexibility and process, product and expansion flexibility in the dynamic aspect were characterized as strategic flexibility.

Barad and Nof (1997) also proposed a hierarchy of flexibility levels in terms of basic, system and aggregate flexibility. Firstly, the basic flexibilities were associated with hardware components, including machine flexibility and material handling flexibility. The system flexibilities were concerned with the composition of the basic flexibility components and related to the tactical decision level. The flexibilities classified in the second category encompassed process (or mix) flexibility, routing flexibility, product flexibility and volume flexibility. Finally, aggregate flexibilities are production flexibility, programme flexibility and market flexibility, derived from Sethi and Sethi's (1990) classification, however, slightly different to them.

An input-process-output (IPO) classification of manufacturing flexibility proposed by this research, illustrated in Figure 2.2, could be a more straightforward one. It is consistent with a general concept of a system. A system employs some basic kinds of resource to constitute a set of various production procedures in the forms of processes and produce a number of outputs to satisfy customers' demands.

Key: L: Labour; M: Machine; MH: Material Handling System; O: Operation; C: Component; P: Product

Figure 2.2: A conceptual framework of Input-Process-Output Classification of flexibility types

From an output perspective, since customers' demands are varied in the forms of different kinds of products and different volume of orders, a flexible system is therefore considered as having the ability to change the product mix, introduce new products and change the production volume. It is intuitive that the flexible system should have product flexibility, production flexibility, volume flexibility and expansion flexibility.

Output-orientated flexibility is based on the whole processes of the system. This concerns the arrangements of the production process in terms of process planning, routing planning and schedule planning. The requirements related to this flexibility are process flexibility, routing flexibility, operation flexibility and programme flexibility.

Those process arrangement capabilities should partly come from the flexibility of their resources. If there is no flexible resource, it could be very difficult to build the flexibility into the system. Generally, there are at least three kinds of resources, namely machines, labours and material handling systems. Therefore, a system is required to have machine flexibility, labour flexibility and material handling flexibility.

In order to explain the conceptual framework of the flexibility structure within a manufacturing system the flexibility types illustrated in Figure 2.2 can be defined as follows:

1. Machine flexibility: the ability of a machine to perform a wide range of operations quickly and economically.
2. Labour flexibility: the ability of a worker to perform a wide range of operations quickly and economically.

3.Material handling flexibility: the ability of a material handling device to transfer a wide range of components and connect a number of machines or machining centers quickly and economically.

4.Operation flexibility: the ability of a system to perform an operation with a number of alternative resources, manpower or facilities etc.

5.Process flexibility: the ability of a process to produce a wide range of parts/products or part/product families quickly and economically.

6.Routing flexibility: the ability of a system to produce a part/product with a wide range of alternative efficient routes.

7.Programme flexibility: the ability of a system to produce a wide range of parts/products untended within a certain period of time.

8.Production flexibility: the ability of a system to handle a wide range of products quickly and economically.

9.Volume flexibility: the ability of a system to produce a wide range of volumes for a product quickly and economically.

10.Product flexibility: the ability of a system to introduce and/or modify a range of new products to the market quickly and economically.

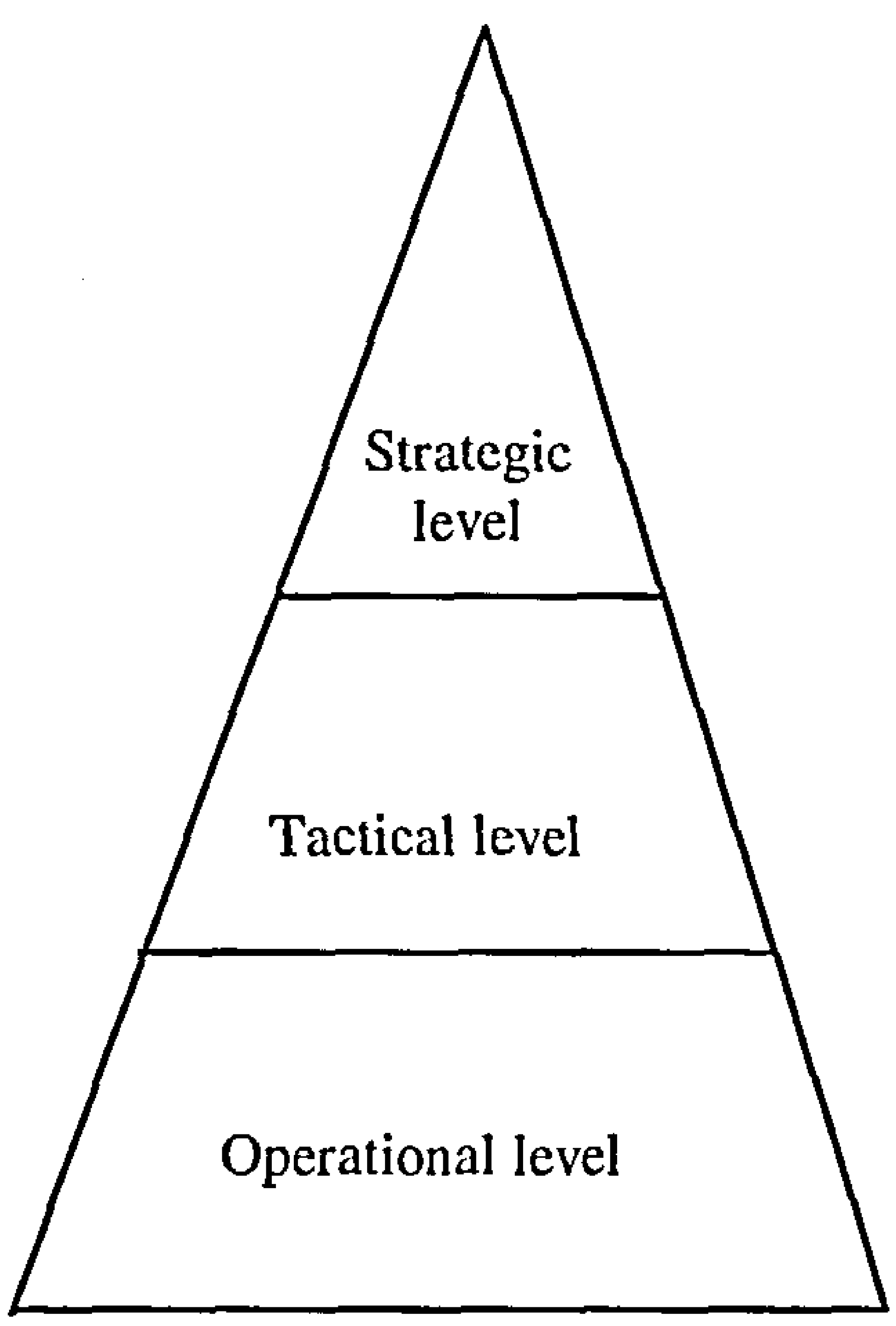
11.Expansion flexibility: the ability of a system to extend its capacity.

The *ability* defined in each type of flexibility above, could generally be specified as *capability* and *capacity. Capability* relates to a system's ability to produce a wide range of outputs; while, *capacity* refers to the efficient performance of that ability, quickly and economically.

2.2.4 Input-Process-Output classification and decision levels

It is sensible to combine the flexibility types, depicted in Figure 2.3, with the organizational hierarchy. An organization may focus on different objectives, when the manufacturing flexibility has been applied as a strategic factor.

Organization hierarchies



Manufacturing flexibility

- Output Orientated Flexibility
  1. Product Flexibility
  2. Product-Mix Flexibility
  3. Volume Flexibility
  4. Expansion Flexibility
- Process Orientated Flexibility
  1. Process Flexibility
  2. Routing Flexibility
  3. Programme Flexibility
  4. Operational Flexibility
- Input Orientated Flexibility
  1. Machine Flexibility
  2. Labour Flexibility
  3. Material Handling Flexibility

Figure 2.3: Manufacturing flexibility types and organization hierarchies

At the strategic level, managers could focus on its competitive advantage to neutralize disturbance in the environment. Tactical managers are interested in the relationship between flexibility and the performance of the manufacturing systems, whereas operational managers will concentrate on the daily work in operations.

When the flexibility types are expanded to map such an idea, it can be seen that strategic managers will emphasize the output-orientated types of flexibility, including product flexibility, product-mix flexibility, volume flexibility and expansion flexibility. The managers at tactical level will concentrate more on process-orientated types of flexibility, including process flexibility, routing flexibility, programme flexibility and operation flexibility. While operational managers would rather concern input-orientated flexibility, namely machine flexibility, labour flexibility and material handling flexibility.

The discussion of the relationship of flexibility types and the organizational hierarchies also reveals the relationship between flexibility types and their time horizon. It is therefore helpful to identify the measurement factors' considerations, stated in this Section 2.2.2.

2.3 Flexibility measurement approaches

Although considerable work has been done in exploring the area of manufacturing flexibility, no consensus operationalized applications have been accepted in academic circles, and hence operational measures present a critical field of priority research (Gerwin, 1993). Sethi and Sethi (1990) thought that the approaches proposed in the literature were too simple or arbitrary to measure. The measures needed to be considered more thoroughly. Researchers, (such as Chen and Chung, 1996), still argue that little work has been done on the area of operational measurement for manufacturing flexibility.

In order to summarize the manufacturing flexibility research and to make a clearer understanding of the operational measures in the literature, Gupta and Goyal (1989) summed up the literature with six measurement approaches: (1) economic consequence, (2) performance criteria, (3) multi-dimensional, (4) Petri-Net, (5) information theory, and (6) decision theory. Moreover, they divided them further into quantitative and qualitative indicators and theoretical and non-theoretical measures. Some further researches after Gupta and Goyal's (1989) survey will be added.

Economic consequences basis measures were concerned with the losses or reduction related to productivity factors in terms of cost, output, throughput rate etc. The works of Mandelbaum (1978), Buzacott (1982) and Son and Park (1987) are included in this area. Chyssolouris and Lee's (1992) approach of sensitivity to change belongs to this category.

The performance criteria based measures focus on ensuring a high level of the selected performance criteria, such as productivity (Zelenovic, 1982), time (Barad and Sipper, 1988), flexible capacity with parallel production lines (Gustavsson, 1984), costs and benefits of alternative processes technologies (Chatterjee et al., 1984), costs incurred for obtaining strategic performance (Azzone and Bertele, 1987), tasks, range, time and cost performances (Carter, 1986), the ratio of available units to the total units in the system (Primrose and Leonard, 1986), and the ratio of setup time to processing time (Falkner, 1986).

The multi-dimensional approach concentrates on the consideration of the measurement criteria in terms of range, time and cost (Slack, 1983). The range is defined as the envelope of the states within a production task set that a system is able to perform. The time is the time required to change between the states, while the cost is depicted by the costs required to make the changes. Gupta and Buzacott (1987) further proposed sensibility, the magnitude of tolerable change, and stability, the magnitude of accommodating high performance with change. Carter's (1986) measures on machine flexibility and routing flexibility and mix flexibility actually embodied the same considerations. Gerwin (1993) and Chang et al. (1998) suggested the same idea.

The Petri-Net approach is based on the time required for system adaptation to the changes (Barad and Sipper, 1988). The application is focused on the evaluation of operation flexibility of a Flexible Manufacturing System (FMS).

The information approach is based on the alternative options or choices available and the freedom of the choices. The greater the number of choices, and the greater uniformity of the probability of the choices leading to greater entropy, meaning the greater flexibility of the system. The works of Yao (1985), Kumar (1986, 1987), Benjaafar and Talavage (1992a), Benjaafar and Talavage (1992b), and Chang et al. (1998) pertain to this area.

The decision theoretic approach suggested that the necessity for flexibility comes from the uncertainty of the future environment. As long as there is uncertainty, difficulty in predicting future events, there is a need for flexibility, and vice versa Mandelbaum and Buzacott (1986). Hutchinson and Sinha (1989) proposed to apply the standard deviation of demand as a measure of uncertainty and concluded that flexibility increased with the increase of uncertainty. Brill and Mandelbaum (1989) applied the theory of probability which represents the changes occurred from the manufacturing environment, to the measurement of manufacturing flexibility. This approach is concerned with the decision making of the managers who will assign the probability to the tasks they are pursuing according to their perceptions about the future.

In all, from an overview of Gupta and Goyal's (1989) work, some shortcomings exist. Some works actually involve different categories. For instance, when discussing the multi-dimensional approach -- range, time and cost, those dimensions may be included in the factors of performance criteria based measures and come across to an involvement of economic consequence criteria based measures. The Petri-Net approach uses time as the basic elements for the measurement that is related to the time dimension. The information approach, which is characterized by increasing the number of choices and unifying the degree of freedom of the choice enabling an increase of flexibility of a system, actually depicts the range dimension.

In De Toni and Tonchia's (1999) recent survey of manufacturing flexibility in the literature, they classified the measurement approaches into direct, indirect and synthetic measures. Direct measures applies the measurement indicators directly related to the meaning of manufacturing flexibility. Such kinds of measures are further divided into direct objective measures and direct subjective measures. The evaluation of the possible options, such as decision theoretic approach and entropy approach, classified by Gupta and Goyal (1989), and the output features, such as Feigenbaum and Karnani (1991), were pertaining to the former category. Gerwin and Tarondeau's (1989) work was associated with the latter, in which they developed questionnaire to survey opinions on various aspects of manufacturing flexibility.

As difficulties were encountered in obtaining direct data, indirect measures were suggested by Gerwin (1987), Slack (1987) and Silvestro (1993). The evaluation with indirect indicators characterized the measurement approaches from the viewpoint of (1) manufacturing system characteristics, and (2) the performance related to flexibility.

System characteristics were related to the forms of choice (techniques, methods, and criteria), including decision choice and managerial choice, to obtain flexibility. Therefore, the measures of flexibility associated with this category concerned technological and managerial ones. The indirect indicators, such as the number of unique parts, the number of part families, and the average time of changeover, were suggested by Ettile and Penner-Hahn (1994).

The performances were divided into economical (cost or value) performances, including Buzacott (1982), Gupta and Buzzacott (1989) and Son and Park (1987), and non-cost (time aspects, quality or service applications) performances. In non-cost performance, the authors did not specify the reports which were pertaining to such a classification, due to the difficulty of finding direct casual relationships between flexibility and a single variable of non-cost performances.

The synthetic measures aggregate the partial measures of the flexibility of a manufacturing system. The reports referred to by the authors were Brill and Mandelbaum (1989) and Jordan and Graves (1995).

It is quite obvious that Gupta and Goyal's (1989) classification is more comprehensive than De Toni and Tonchia's (1999) work from the viewpoint of the measurement perspective. It seems that Gupta and Goyal's (1989) classification can cover De Toni and Tonchia's (1999).

2.4 Dimensional approach to the measurement

Table 2.2 showed that widely different definitions of each type of flexibility have been proposed by different researchers. Although these definitions are a synthesis of many researchers' viewpoints, it can be seen that they did not propose a consistent, easily computable rule for the measurement of manufacturing flexibility.

Following from the proposed definition of each type of flexibility, many researchers have tried to develop approaches for the measurement of manufacturing flexibility. The chosen factors for the measurement mainly adopted the viewpoint of Slack (1983) and Gerwin (1987, 1993). Three dimensions, namely range, cost and time, have been suggested as the consideration in the measurement models. The range is defined as the set of alternative sizes of tasks for the option; whereas, time refers to the duration required of the system to change to perform different tasks, and cost is the penalty of the changes.

In most circumstances, Slack (1989) stated that cost and time overlap to some degree and time seems to be more important than cost. Barad and Sipper (1990), Barad (1992), Crowe (1992), and Upton (1994) echoed the same viewpoint. Barad and Nof (1997) suggested a similar idea and reviewed flexibility measures with two dimensions, namely range and time.

This research, however, argues that time and cost are not a complete trade-off. Some efficient production could be achieved by massive investment for saving time, some others by focusing on rather traditional equipment to save cost but consume more time. It should depend on what strategy a system has chosen. Although time has emerged as an important factor in the competitive environment, some companies in some industries may choose low cost as their competitive edge.

After reviewing the relevant literature in this field, this research extends each type of flexibility with three dimensions: time, range and cost, and this has been illustrated in Table 2.3. Therefore, the measurement of manufacturing flexibility needs to consider the range of output tasks, the time required for changeovers and the cost spent on the changeovers.

Three-dimensional flexibility factors reveal a more specific and quantitative way of approaching the proposal of the measurement models. However, they show that researchers seem less interested in the cost dimension when measuring flexibility. Maybe this phenomenon is coincident with Slack's (1989) statement:

...Both cost and time can be regarded as the 'fiction' elements of flexibility which constrain the response of the system. They are the manifestations of the difficulty of making a change. In fact, when assessing the flexibility processes, time is usually more important than cost....

Table 2.3: A review of measurement methods of flexibility with three dimensions

Three Dimensions / Flexibility Type	Range	Time	Cost
1.Machine Flexibility	1.Number of different operations performed by machines weighted by the importance of tasks (Brill and Mandelbuam, 1989) 2.Extent of variation in the inputs that the machine can handle (Gerwin, 1987) 3.The number of different operations that a machine can perform without a prohibitive time to switch. (Sethi and Sethi, 1990) 4.The range of possible dimensions that a machine is able to perform. (Carter, 1986) 5.The proportion of operations of a part that can be performed by a machine. (Nagarur, 1992)	1.The time needed to replace tools (Browne et al. 1984) 2.The time needed to change tools in a tool magazine (Browne et al. 1984) 3.The time needed to assemble or mount a new fixture (Browne et al. 1984) 4.The time required to changeover to different operations (Carter, 1986) 5.The ratio of setup time to processing time (Falkner, 1986) 6. The reciprocal of operation processing time (Chen and Chung, 1996; and Brill and Mandelbaum, 1989) 7.The time required in switching from one operation to another. (Taymaz, 1989; and Chandra and Tombak, 1992)	1.Cost of switching from one operation to another (Taymaz, 1989; and Sethi and Sethi, 1990) 2.The ratio of the total output and idle cost of the machine for a given period (Son and Park, 1987) 3. The cost incurred in making the changeover (Carter, 1986) 4. Total cost function of variable costs, inventory holding costs, raw material holding costs, fixed costs, and setting costs
2.Labour Flexibility	1.Readiness with which the number of workers can be changed. (Atkinson, 1985) 2.The number of different types of task performed by the worker (Atkinson, 1985) 3.The number (or percentage) of CNC-trained workers. (Jaikumar, 1984)	1.Time needed by compensation schemes to allow changes in labour. (Atkinson, 1985) 2.Time needed by workgroup to handle breakdowns and rerouting.	
3.Material Handling Flexibility	1.Ratio of the number of paths available in a system to the number of all possible paths. (Chatterjee et al. 1984; Sethi and Sethi, 1990) 2.The important characteristics of the devices and the weight of these characteristics, used to obtain a measure of their material handling flexibility. (Klahorst, 1981)		

Flexibility Type \ Three Dimensions	Range	Time	Cost
4.Process Flexibility	1.The number of part types that can be processed simultaneously without batches. (Browne et al., 1984) 2.The volume of the set of part types that the system can produce without a major setup (Browne et al., 1984; Gerwin, 1987) 3.The extent to which product mix can be changed while maintaining efficient production (Carter, 1986) 4.Average number of possible ways in which a part type can be processed in the system (Chatterjee et al., 1984)	1. Average processing time per part (Jaikumar, 1986) 2.Average changeover time (Ettlie, 1988) 3.Average changeover time compare to average cycle time of machine (Carter, 1986) 4.Setup times for producing a given product mix (Assone and Bertele, 1989)	1.Changeover cost between different known jobs within the current production plan. (Wernecke and Steinhilper, 1982) 2.Expected value of a portfolio of products for a given set of contingencies (Jaikumar, 1984) 3.The ratio of the total output and the waiting cost of parts processed for a given period. (Son and Park, 1987)
5.Routing Flexibility	1. Average number of ways in which a product (part) can be made. (Chatterjee et al., 1984; Chung and Chen, 1989) 2. Routing entropy: the information contained in the list of operation and the machines which could be chosen. (Yao and Pei, 1990; Kumar, 1986, 1987) 3. The ratio of the existing number to the possible number of links between machines in the given system. (Carter, 1986) 4.The ratio between its expected production and the production of the fully operating system (Azzone and Bertele, 1989) 5.The number of alternative routings that are available for a part (Zahran et al, 1990) 6.The proportion of all potential routes that are available for each part (Nagarur, 1992) 7.The average number of alternative routes for processing a part type (Sinha and Wei, 1992) 8.Actual routing flexibility is the number of existing production routes for a part; while potential routing flexibility is the total number of available routes to make a given part (Bernado and Tombak, 1992) 9.The ratio of actual paths to the ideal paths of the system (Primerose and Leonard, 1986)	1. Percentage decrease in the throughput because of machine breakdowns. (Buzacott, 1982) 2. Percentage reduction in total job completion time due to the presence of machine breakdowns when compared with use of fixed routes. (Chung and Chen, 1989) 3.Decrease in throughput because of a machine breakdown (Gerwin, 1987) 4.Time-based efficiency rating of each route (Zahran et al., 1990) 5.Time-based efficiency - the ratio between the processing time and that of the shortest route. (Das, 1996) 6.Throughput time (Falkner, 1986)	1.Cost of production lost due to rescheduling or urgent jobs. (Browne et al., 1984) 2.The robustness of the system when breakdowns occur. (Browne et al., 1984)

Three Dimensions / Flexibility Type	Range	Time	Cost
6.Programme Flexibility	1.Number of systems with untended operations. (Jaikumar, 1984) 2.Scale of measuring automation level ranging from 1 (lowest) to 17 (highest) (Bright's, 1958)	1.Expected percentage uptime during second and third shifts. (Jaikumar, 1984) 2.Time needed to generate a new programme for part production or changing production system.	
7.Operation Flexibility	1. The number of interchange the ordering of several operations for each part type. (Upton, 1994) 2. Number of different process plans for a part (Sethi and Sethi, 1990)	1.Machine downtime (Falkner, 1986) 2.The entropy value of performing an operation with processing time consideration (Kumar, 1986, 1987) 3. The setup time needed to interchange the ordering of several operations for each part type. (Upton, 1994)	
8.Production Flexibility	1.The universe of part type that the system can produce. (Browne et al., 1984) 2.Lot size (Cox, 1989) 3.Size of the universe of parts the manufacturing system is capable of producing without adding capital equipment (Chatterjee et al., 1984) 4.Extent to which product mix can be changed while maintaining efficient production (Carter, 1986) 5.The number of products the company produces (Muramatsu et al., 1985; and Bateman et al., 1999) 6.The size of parts produced by the system (Assone and Bertele, 1989)	1. Production cycle time (Cox, 1989) 2.Setup time for each product mix (Cox, 1989) 3. Throughput time 4. Time needed to setup a production line. (Barad and Sipper, 1988) 5.The time required to switch from one part mix to another (Buzacott, 1982; Browne et al., 1984) 6.Changover time (Bateman et al, 1999)	1.Cost to change from one product (part mix) to another. (Buzacott, 1982; Browne et al., 1984) 2.Changeover cost (Chryssolouris and Lee, 1992) 3.Work-In-Progress inventory (Cox, 1989)
9.Volume Flexibility	1.The minimum volume of all part types for which the system can be run profitably. (Browne et al., 1984) 2.The range of volume of all part types that the system can run profitably. (Sethi and Sethi, 1990) 3.Ratio of average volume fluctuations to total capacity. (Gerwin, 1987) 4.The average number of feasible routes that a part type can flow through the system (Chen and Chung, 1996)	1.Time required to increase or decrease production volume by 20%. (Sethi & Sethi, 1990) 2.Potential Requirement Ratio (PRR): the amount of slack capacity, where PRR= total available time - (required time + maintenance time)/ required time (Ancelin, 1986) 3.The percentage decrease in throughput due to the machine breakdown (Buzacott, 1982; and Browne et al., 1984)	1.Stability of manufacturing costs over widely varying levels of production volume. (Falkner, 1986) 2.The ratio of the total output and the inventory/storage costs of finished products and raw materials for a given period. (Son and Park, 1987) 3.The slope of short-run average curves (Stigler, 1939; and Marschak and Nelson, 1962)

Three Dimensions / Flexibility Type	Range	Time	Cost
10.Product Flexibility	1.Number of parts made per year (Jaikumar, 1986) 2.Number of part types made per year (Jaikumar, 1986) 3.Number of products made per year (Jaikumar, 1986) 4.Number of products types made per year (Jaikumar, 1986) 5.Number of new parts introduced per year (Jaikumar, 1986) 6.Size of the universe of parts the manufacturing system is capable of producing without adding major capital equipment (Chatterjee et al., 1984)	1.Time required to introduce new products (Sethi & Sethi,1990)	1.Ratio of total output to setup costs.(Son and Park, 1987) 2.Cost required to introduce new products ((Assone and Bertele, 1989; and Sethi & Sethi, 1990) 3.Total incremental value of new products that can be fabricated within the system for a 20% additional cost in new fixtures, tools and part programmes. (Jaikumar, 1984)
11.Expansion Flexibility	1.Upper limit on the amount of capacity expansion. (Browne et al., 1984)	1. Time needed to double the output of the system. (Carter, 1986) 2. Time required to add a unit of capacity. (Sethi and Sethi, 1990)	1.Maximum possible size of the system. (Browne et al., 1984) 2.Cost of doubling the output of the system. (Carter, 1986) 3.The cost of acquiring a machine (Assone and Bertele, 1989)

2.5 Flexibility needs

Extended from the measurement of each type of manufacturing flexibility, Gerwin (1993) pointed out that it is necessary to analyze the need for flexibility in industry in further detail. The dimensions of each type of flexibility have been categorized as required, potential and actual. The classification may help managers to determine the level at which their system is currently performing, what is the gap that they need to bridge, and what is the achievable level of their flexibility. Gerwin's (1993) work can be characterized as in Figure 2.4.

The idea illustrated in Figure 2.4 is an outline of the relationship between flexibility types, flexibility dimensions and flexibility needs. It also depicts the structure of manufacturing flexibility. For each flexibility type, it is necessary to consider its dimensions, namely cost, time and range. Moreover, in order to obtain a proper management of manufacturing flexibility, it seems necessary to take into account the needs at each dimension of flexibility type. It could not be necessary to have the highest level of flexibility in every type or in its systems, as they may conflict with each other and cause an unnecessary increase in other performance factors.

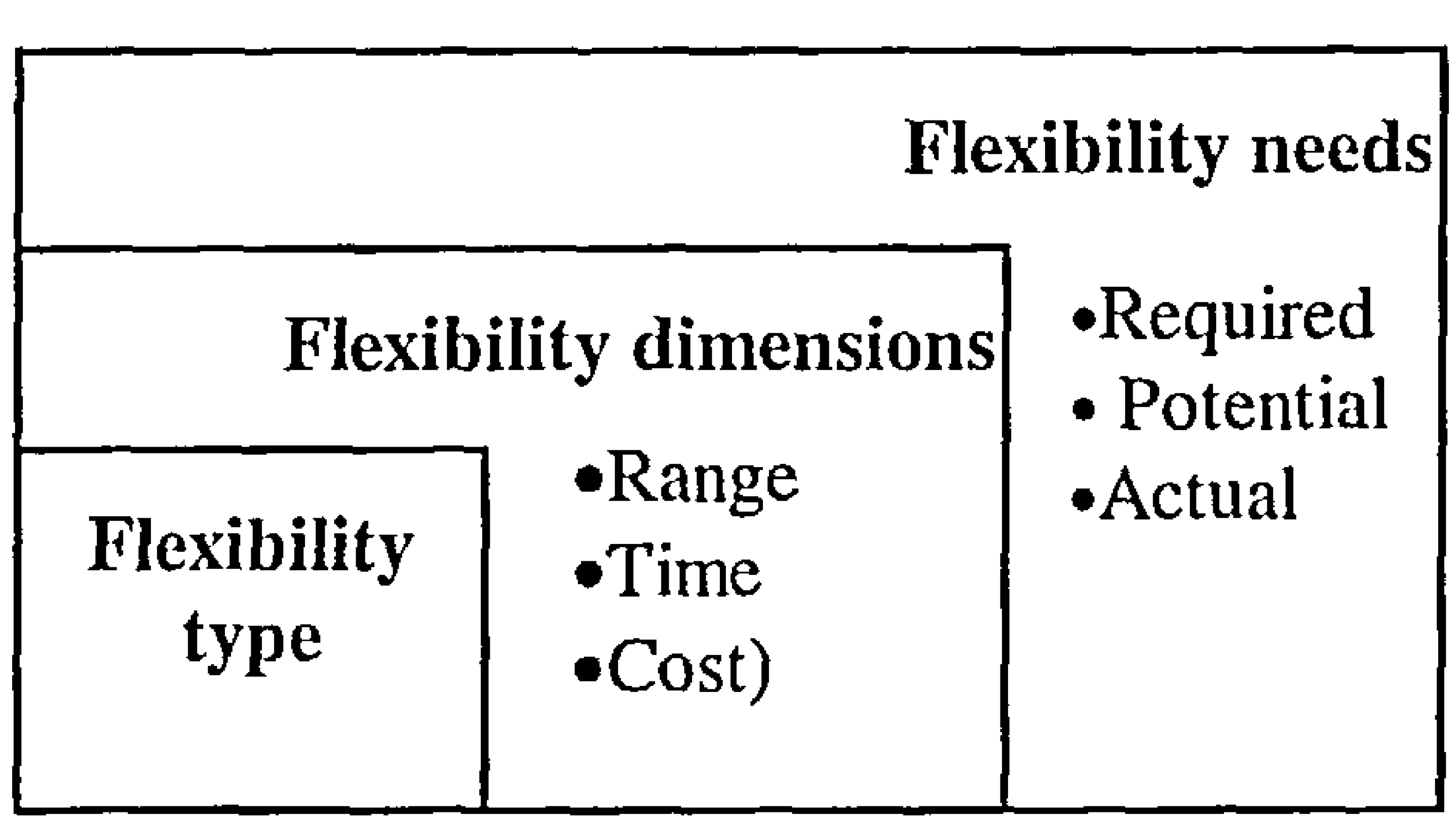


Figure 2.4:The relationship between flexibility types, dimensions and needs

There are three levels of needs for each type of flexibility, namely required level, potential level and actual level. The required level of system flexibility depicts the requirements a system must give its customers, or those needed to compete in the marketplace. This is determined by the managers.

The potential level of flexibility is the designed ability of the system or an indication of the system's potential behavior. This ability is not currently seen, but will be exhibited in the future. Gupta and Goyal (1989) considered that flexibility should be some kind of potential rather than present performance. Upton (1995) and Slack (1989) had a similar viewpoint. They thought the value of the flexibility lies in the potential ability of the system, not in the exhibited one, because flexibility is for coping with environmental uncertainties and the nature of such uncertainties is difficult to predict. When there is no environmental uncertainty, it is not necessary to build flexibility into the system. Hutchinson and Sinha (1991) reached the same conclusion. Therefore, it is necessary to pay attention to the un-exhibited ability of the system. The actual level of flexibility is the actual outcomes in the daily operations, exhibited by the utilization of the system and determined on the basis of experience.

Das (1996) also suggested that flexibility measurement should take into account different levels of measures, namely necessary, capability, actual, inflexibility, and optimality flexibility. Necessary flexibility is consistent with Gerwin's (1993) required level of flexibility, meaning a set of states that a company needs to attain for competing with the expected changes in the marketplace. Capability flexibility is the ability that the system has been designed with, which is related to Gerwin's (1993) potential level of flexibility. Actual flexibility of a system is the demonstration of the actual performance on flexible production. The inflexibility of the system is measured by the difference between the necessary flexibility and capability flexibility. Finally, the optimal flexibility captures the difference between the optimal or best state of performances which should be attained by the system in response to the changed conditions and the actual attained state of performances of the system.

2.6 An extended framework of manufacturing flexibility research

As can been seen, the research in the manufacturing flexibility literature is quite complicated and chaotic. Any possible measure could be proposed, as long as the approach is able to depict the meaning of flexibility reasonably in its own way. The main reason is that there is no consensus on the types of flexibility classification and no acceptable unified measurement approaches.

In addition to the four streams of the research in the literature, illustrated in Figure 2.1, this thesis has added two more streams, namely flexibility attributes and flexibility at different system levels, as depicted in Figure 2.5. It is hoped that this would provide a more thorough treatment of manufacturing flexibility.

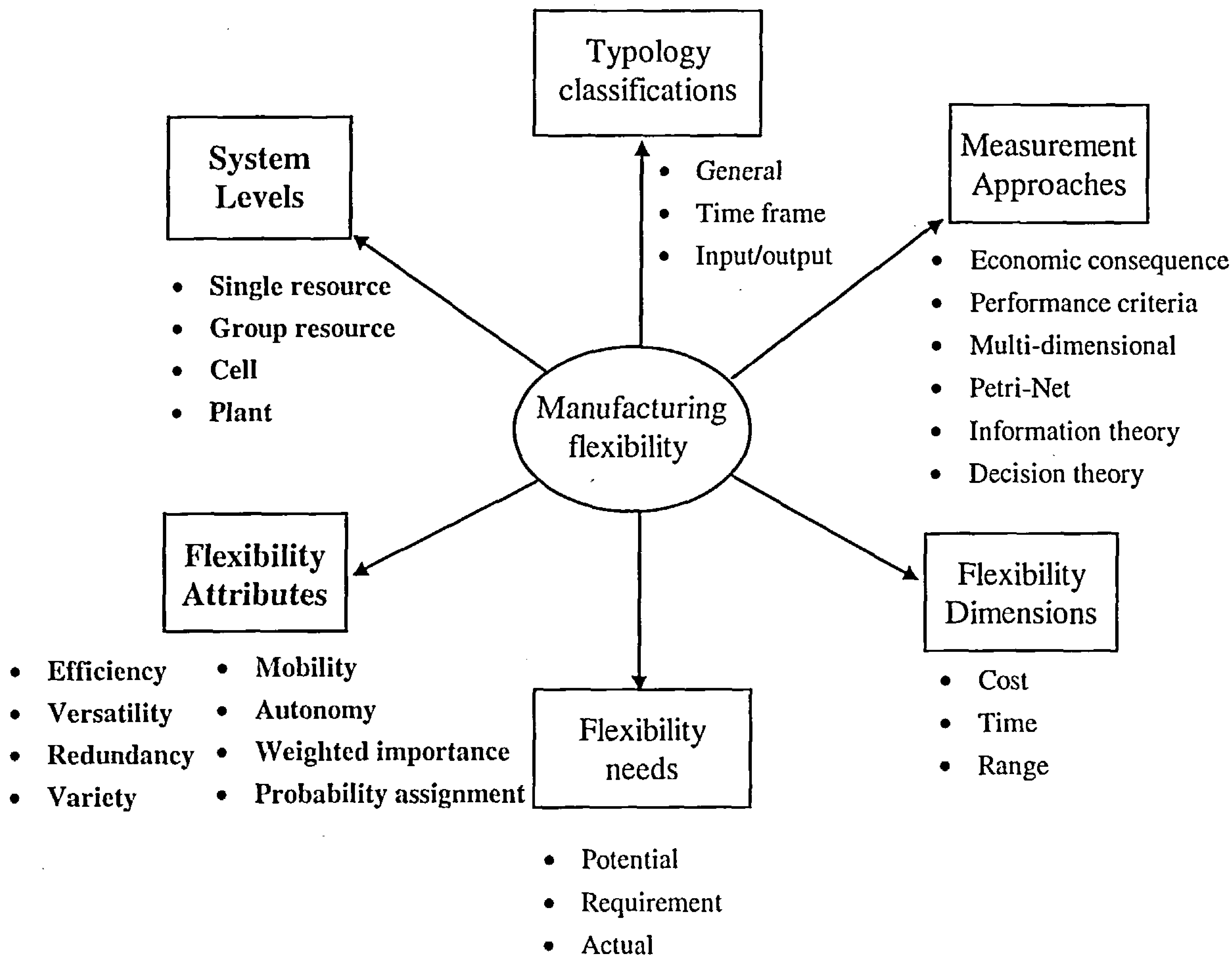


Figure 2.5: An extended framework of manufacturing flexibility research (Bold indicates the extension)

2.7 Flexibility attributes

In the surveyed literature, the proposed models applied only a part of the attributes contained in flexibility. In other words, researchers have used partial attributes to explain the meaning of manufacturing flexibility, and these contradictions have resulted in different measurement approaches. Bias and other shortcomings appear in the proposed measurement models.

This research suggests another way of considering flexibility measurement in manufacturing systems. The conceptual framework proposed by this research contains multi-attribute characteristics to depict the meaning of flexibility in manufacturing systems. **Research into the measurement of manufacturing flexibility should consider all the attributes in the model; otherwise, the results of the assessment could lead to a partial solution and increase confusion. It could be that researchers have not recognized such a characteristic within the flexibility concept and this has caused the confusions concerning manufacturing flexibility measurement in the literature.**

There are three categories of flexibility attributes proposed in the present research, namely physical attributes, managerial attributes and decision attributes. The first category is divided into two sub-categories in terms of: 1) basic attributes, including efficiency and versatility, which are directly related to system effectiveness; and 2) supportive attributes, including redundancy, variety, mobility and autonomy, which will sustain the efficiency and versatility. The second category includes control and learning, which will contribute to those physical characteristic attributes. However this research will not include these two attributes in the measurement models. The third category includes output task probability assignment and the weight of importance of the outputs.

Efficiency is always the core issue of management concern. Due to the involvement of a complicated environment, the assessment of efficiency must consider more than just economic orientated criteria. This also makes efficiency a complex concept. Cost-based and time-based efficiency evaluations will be distinguished. The Data Envelopment Analysis (DEA) is the chosen approach to apply to efficiency measurement.

The entropy approach, which has the states that the greater the number of available options, the larger the entropy value, will be applied to the measurement of versatility and redundancy. Mobility measures the ability of a resource to move, including the coverage area of the movement in the system and the number of the other resources which can be substituted. Autonomy is the measurement of the percentage of completing the output tasks by the evaluated system.

The attribute of probability of occurrence assigned to the output tasks and the weights of importance are related to the requirement of management for managers to do their decision making. The probability of occurrence refers to the likelihood of appearance in the future market. The weights of importance are related to the tasks that the goals should be established by the firms for their strategy considerations.

Attributes description illustrates a better understanding of the concept of flexibility of a manufacturing system. The exploration into flexibility attributes could provide a more holistic treatment on the measurement of manufacturing flexibility. Although a unified framework of flexibility measurement is not provided by this research, it could render a more thorough considerations, when it is investigated into flexibility concept embodied in the different system levels or flexibility typologies. The attributes scheme will be developed in detail in Chapter 3, and their measurement approaches, methods and models will be illustrated in Chapter 4.

2.8 Flexibility attributes and system levels

The flexibility within a manufacturing system has been characterized by types and different hierarchical levels. It has been proved that they influence each other, and that the lower level of flexibility is able to support the higher level of flexibility. For instance, machine flexibility can improve routing flexibility, volume flexibility, process flexibility, production and product flexibility and expansion flexibility. Such a phenomenon can also be seen between different system levels. Gerwin (1987) proposed that the measurement of manufacturing flexibility should take into account the domain of the flexibility concept at different levels in the following situations: (1) the individual machine or manufacturing systems; (2) the manufacturing function; (3) the manufacturing process; (4) the factory; and (5) the entire factory system of the company. Gupta (1993) also stated that single machine flexibility is able to improve flexibility at cell and plant levels.

The attributes embodied in the concept of flexibility have been demonstrated above. However, some aspects will deviate, when they are applied to different system levels, namely the single resource level, group resource level, cell level and plant level. Figure 2.6 exhibits the possible assignment of the proposed attributes to the four different levels. It shows two common aspects existing at all levels of the system. One aspect is that efficiency and versatility, which are defined as two basic attributes in the present research, and variety appear at all levels. It illustrates that a flexible system should have the ability to perform efficiently a wide variety of functionally differentiated tasks. The other aspect is that, from an effective orientated consideration, there is a need to consider exogenous factors, namely weighted importance and the probability of doing the tasks which need to be performed by the resource. This means that a flexible system should have the ability to cope with the dynamic changes assigned by the manager in order that it can compete effectively in the marketplace.

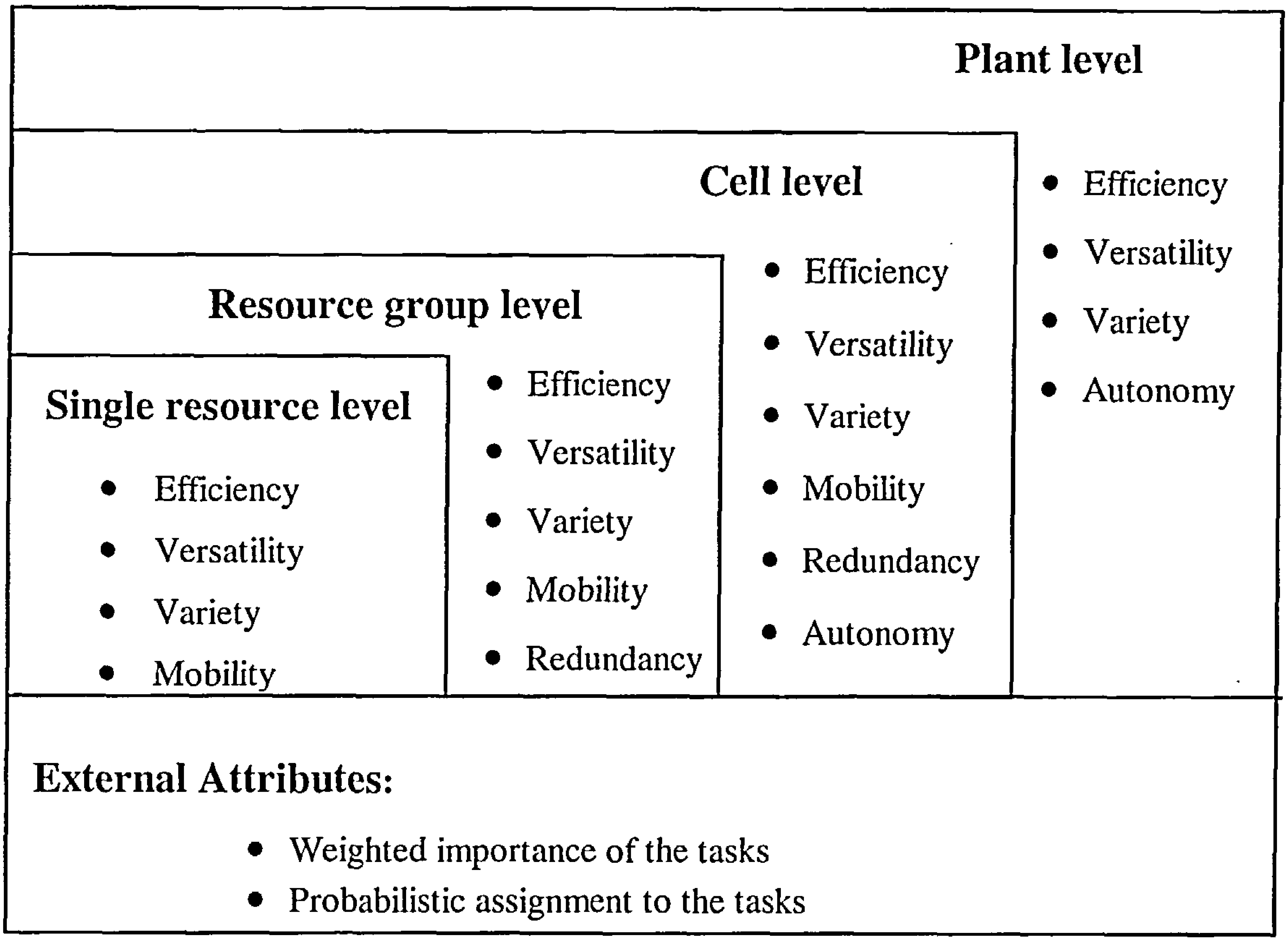


Figure 2.6: A developed scheme of factors for manufacturing flexibility measurement

2.8.1 Single resource level

At the single resource level, Chang et al.'s (1998) proposal of the revised entropy approach, which combined efficiency and versatility as the flexibility measurement of a single machine, was a good initial stage to lead to a consideration of attributes embodied in the flexibility concept of a manufacturing system. However, Gupta (1993) thought that it is necessary to take further account of the differences among the outputs of the task set which the machine is capable of performing. Such a consideration is defined as variety in the present research, and can be considered as an additional attribute to the measurement of a single resource's flexibility. Mobility of a resource is its ability to move. Mobile resources enhance a system's ability to cope with many types of changes encountered by the system, e.g., volume change, product-mix change, new product introduction and so forth.

Efficiency measurement, at the single resource level, requires to take into account setup times and process times and setup costs and process costs for the operations that the resource is capable of performing, while versatility needs to consider the number of operations. Variety, which reflects the differences between operations, is measured by the average of the percentage of commonality among the operations. Mobility is measured by the time and cost usage for the movement of the resource.

2.8.2 Resource group level

When the same kind of resources are grouped together, at group resource level, redundancy, in forms of excess capacity, capability and/or utility, is an additional factor in making the system flexible. If the system is not certain to operate 100 percent reliably, redundancy has to be added to the system.

Redundancy, on the one hand, has a positive effect on flexibility, since it is the same as Kumar's (1986, 1987) alternative options of resources to the particular task viz. entropy within groups of operations. The greater the options for the task, the more the redundancy of the resources and hence the higher the value of flexibility. In short, redundancy considers the number of resources which are capable of doing one particular task.

However, on the other hand, it seems implausible to simply sum the same kind of individual flexibility of resources to evaluate the group resources' flexibility. Actually, redundancy is partly a negative factor in group resource flexibility, because the system needs to invest more resources for producing the tasks (Slack, 1989). It has a negative effect on the efficiency of the system.

Efficiency, versatility, variety and mobility at the single resource level will all contribute to group resource flexibility. The measurement of the attributes at the group resource level has the similar considerations to those at the single resource level.

2.8.3 Cell level

When the measurement of flexibility is expanded to include different kinds of resources for constructing a manufacturing cell, there is the further consideration of autonomy. At cell level, the system generally consists of some machines, operators, transportation equipment and devices, and/or cell controller for an advanced manufacturing system. They are grouped together to produce a certain mix of parts/products or part/product families. The physical components within the cell will contribute their flexibility to the cell level.

Flexibility measurement at the cell level is focused on the completion of the set of parts/products or the part/product family. Efficiency takes into account the times and costs for setting up the cell and performing the operations on the parts/products or part/product family. Versatility is concerned with the number of parts/products or part/product families performed by the cell. Moreover, variety takes into account the difference among the parts/products or part/product families, while redundancy is the ability to reroute the production of parts/products or part/product family.

After a certain period of time, however, the mix of parts/products or part/product families could be changed by the decision makers to meet customers' needs. It could become necessary to rearrange the production layout, meaning production procedure changes or facilities position changes to retain the system's high efficiency. As a result, mobility appears to be an important consideration at the cell level. The measurement of mobility at the cell level is proposed to be the effort, in terms of time usage and cost consumption, of rearranging the new layout of the cell.

A cell is constructed to independently produce a specific group of parts/products or a part/product family. One of the effects is to reduce inter-cell movements, which might reduce the efficiency of performing the tasks. To perform the tasks independently depicts the ability of autonomy. In all, a flexible cell is expected to efficiently complete a wide and functionally different range of outputs and with little or no assistance from other cells. Therefore, the autonomy measurement at cell level is to be expressed by the ratio of time spent in the cell to the total lead time of producing the parts/products or part/product family.

2.8.4 Plant level

The cells' flexibility will contribute to the plant level flexibility. However, it should be noted that to sum up the physical characteristics is not likely to depict the flexibility at plant level as well. The ideas developed at the cell level are all applicable to this level and are able to be expanded to a wider consideration in the scope of the system.

At plant level, there are multi-aspects of abilities required to show a plant which is flexible, e.g., a wide and varied range of products produced efficiently by the plant, the speed of introducing new products, and the ease of accommodating demand fluctuations etc. The efficiency attribute at plant level corresponds to the time and cost spent on setups and processes for producing the product mix and introducing new products, compared to the theoretical value or the best practice in the peer industry or the time and cost needed to change production rates, or compared to the most efficient production volume. Versatility of the plant is interpreted by the range of product mix, the number of new products introduced in a certain period of time, and the profitable range of production volume and so forth.

Variety reflects the differences between the output products, the new products and the increasing rate or decreasing rate of production volume. It is unlikely to be necessary to take redundancy into account at this level as it has been incorporated in the efficiency measurement. In addition, mobility is also already embodied in the consideration of setups for the product mix or new product introduction.

Autonomy is an another attribute which must be taken into consideration in some circumstances, when the decision of a plant is to buy some components from its suppliers. Thus it appears that the plant makes a lower percentage of products components, meaning that the plant calls for assistance from its suppliers, and this shows the reduced autonomy of the plant.

2.9 Concluding remarks

Gerwin (1993) suggested that the first major point in developing an agenda for research in this field is that research on manufacturing flexibility needs to have both theoretical and applied orientations. The latter seems more important than the former, because of the scarcity of the latter. Research into operational flexibility is extremely important, even though to propose unified framework of manufacturing flexibility has been regarded as a very difficult task by researchers.

Up to now researchers as well as managers do not seem to have had a good understanding of manufacturing flexibility. The reasons could be that the measurement factors embodied in the concept of manufacturing flexibility have not yet been clearly identified, and the terms depicting flexibility types have been denoted arbitrarily. This research has summarized the researches in the literature, especially from the point of view of operational applications. The followed sequence is reviewed as flexibility typology classifications, flexibility types definitions, flexibility measurement approaches, flexibility measurement factors and flexibility needs for the applications. This research has also classified flexibility types with an Input-Process-Output conceptual framework for a more straightforward perception of manufacturing flexibility. Moreover, a detailed literature review of three dimensional measurement factors has been illustrated.

However, this research argues that confusion still exists in the literature, due to the partial treatments that have appeared in the measurement approaches. Therefore ten types of flexibility attributes which have been proposed for considering the measurement of manufacturing flexibility. Moreover, there is another need to specify the domain of the evaluated systems at different levels. There are at least four system levels which need to be considered for the measurement. This research project will focus on proposing the flexibility attributes, their measurement methods and models for the applications into the measurement of manufacturing flexibility.

Theoretically, it should be possible to quantify flexibility of a manufacturing system with a unified measurement model for every flexibility type, as long as the type of flexibility measured could be treated as a system. This could be a long way off, but it is worthwhile doing.

2.10 References

Azzone, G. and Bertele, U. (1987), "Comparing Manufacturing Systems with Different Flexibility: A New Approach", *Proceeding of The Decision Sciences Institute*, Boston, pp. 609-693.

Azzone, G. and Bertele, U. (1989), "Measuring the Economic Effectiveness of Flexible Automation: A New Approach," *International Journal of Production Research*, Vol. 27, No. 5, pp. 735-746.

Barad, M. (1992), "Impact of Some Flexibility Factors in FMSs -- A Performance Evaluation Approach", *International Journal of Production Research*, Vol. 30, No. 11, pp.2587-2602.

Barad, M. and Nof, S. Y. (1997), "CIM Flexibility Measures: A Review and a Framework for Analysis and Applicability Assessment", *International Journal of Computer Integrated Manufacturing*, Vol. 10, No. 1-4, pp296-308.

Barad, M. and Sipper, D. (1988), "Flexibility in Manufacturing Systems: Definition and Petri-Nets Modeling", *International Journal of Production Research*, Vol. 26, No. 2, pp.237-248.

Barad, M. and Sipper, D. (1990), "Flexibility and Types of Changes in FMSs: A Timed Petri-Nets Assessment of Machine Flexibility", *The International Journal of Advanced Manufacturing Technology*, 5, pp.292-306.

Bateman, N., Stockton, D. J., and Lawrence, P. (1999), "Measuring the Mix Flexibility of Manufacturing Systems", *International Journal of Production Research*, Vol. 37, No. 4, pp. 871-880.

Benjaafar, S. and Talavage, J. J. (1992a), "Axiomatic Measure of Flexibility in advanced manufacturing systems, 1992 *IEEE International Conference on Systems, Man and Cybernetics*, Vol. 2, #92CH3176-5.

Benjaafar, S. and Talavage, J. J. (1992b), "Process Flexibility in Manufacturing Systems: Models and Measurements", Working paper, School of Industrial Engineering, Purdue University, West Lafayette, IN, August.

Benjaafar, S. and Ramakrishnan, R. (1996), "Modeling, Measurement and Evaluation of Sequencing Flexibility in Manufacturing Systems", *International Journal of Production Research*, Vol., 34, No.5, pp. 1195-1220.

Brill, P. H., and Mandelbaum, M. (1989), "On Measurement in Manufacturing Systems", *International Journal of Production Research*, Vol. 27, No. 5, pp.747-756.

Bright, J. C. (1958), "Automation and Management", Division of Research, Graduate School of Business Administration, Harvard University, Boston, MA.

Browne, J., Dubois, D., Rathmill, K., Sethi, S.P., and Stecke, K.E. (1984), "Classification of Flexible Manufacturing Systems", *The FMS Magazine*, 2 (2), pp.114-117.

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the 1st International Conference on FMSs*, Brighton, UK, pp.13-22.

Chandra, P. and Tombak, M. M. (1992), "Models for the Evaluation of Routing and Machine Flexibility," *European Journal of Operations Research*, Vol. 60, pp. 156-165.

Chang, A.Y., Whitehouse, D. J., Chang, S. L., and Hsieh, Y. C. (1998), "A Revised Entropy Approach to the Measurement of Manufacturing System Flexibility", in *Proceeding of the Joint Conference of The Fifth International Conference on Automation Technology (Automation 98') and 1998 International Conference of Production Research (Asia Meeting)*, Taipei, Taiwan, R.O.C.

Carlsson, B. (1989), "Flexibility and the Theory of the Firm, " *International Journal of Industrial Organization*, Vol. 7, pp.179-203.

Carlsson, B. (1992), "Management of Flexible Manufacturing: An International Comparison", *OMEGA International Journal of Management Science*, Vol. 20, No. 1, pp.11-22.

Carter, M. F. (1986), "Designing Flexibility into Automated Manufacturing System." in *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems (Ann Arbor, MI),* K.E. Stecke and R. Suri (Eds), Elsevier, Amsterdam, The Netherlands, pp.107-118.

Chatterjee, A., Cohen, M. A., Maxwell, W. L., and Miller, L. W. (1984), "Manufacturing Flexibility: Models and Measurements", in *Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.49-64.

Chatterjee, A., Cohen, M. A., Maxwell, W. L., and Miller, L. W. (1987), "A Planning Framework for Flexible Manufacturing Systems", WP #87-07-04, University of Pennsylvania, Philadelphia, PA, July.

Chen, I. J., Calantone, R. J. and Chung, C. H. (1992), "The Marketing-Manufacturing Interface and Manufacturing Flexibility. *OMEGA*, 20 (4), pp.114-117.

Chen, C. H. and Chung, I. J. (1991), "Effects of Loading and Routing Decisions on Performance of Flexible Manufacturing Systems", *International Journal of Production research,* Vol. 29, No. 11, pp. 2209-2225.

Chen, C. H. and Chung, I. J. (1996), "An examination of flexibility measurements and performance of flexible manufacturing systems", *International Journal of Production Research*, Vol. 34, no. 2, pp.379-394.

Chung, C. H. and Chen, I. J. (1989), "A Systematic Assessment of the Value of Flexibility from FMS", in *Proceedings of the Third ORSA/TIMS Special Interest Conference on FMS*, New York: Elsevier.

Chung, C. H. and Chen, I. J. (1990), "Managing the Flexibility of Flexible Manufacturing Systems for Competitive Edge", in M. J. Liberatore (Ed.), *Selection and Evaluation of Advanced Manufacturing Technologies*, Springer-Verlag, New York, pp.280-305.

Correa, H. L. (1994), *Linking Flexibility, Uncertainty and Variability in Manufacturing Systems*, Avebury, Ashgate Publishing Limited, England.

Cox, J. T. (1989), "Toward the Measurement of Manufacturing Flexibility", *Production and Inventory Management Journal*, First Quarter, pp.68-72.

Crowe, T. J. (1992), "Integration Is Not Synonymous with Flexibility," *International Journal of Operations and Production Management*, Vol. 12, No. 10, pp. 26-33.

Das, S. K. (1996), "The Measurement of Flexibility in Manufacturing Systems", *The International Journal of Flexible Manufacturing Systems*, 8, pp.67-93.

De Toni, A. and Tonchia, S. (1999), "Manufacturing Flexibility: A Literature Review", *International Journal of Production Research*, Vol. 36, No. 6, pp. 1587-1617.

Ettile, J. E. (1988), "Implementation Strategies for Discrete Parts Manufacturing Technologies: Final NSF Report", University of Michigan (Ann Arbor, MI: University of Michigan).

Ettlie, J. E. and Penner-Hahn, J. D. (1994), "Flexibility Ratios and Manufacturing Strategy," *Management Science*, Vol. 40, No. 11, pp. 1444-1454.

Falkner, C. H. (1986), "Flexibility in Manufacturing Plant", in *Proceedings of 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, pp. 95-106.

Farrell, M. J. (1957), "The Measurement of Productive Efficiency", *Journal of the Royal Statistical Society A 120*, part 3, pp.253-281.

Frazelle, E. H. (1986), "Flexibility: A Strategic Response in Changing Times", *Industrial Engineering*, March, pp.17-20.

Garrett, S. E. (1986), "Strategy First: A Case in FMS Justification", in *Proceedings of the 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.17-30.

Gerwin, D. (1982), "Do's and Don'ts of Computerized Manufacturing", *Harvard Business Review*, Vol. 60, pp.107-116.

Gerwin, D. (1987), "An Agenda for Research on the Flexibility of Manufacturing Processes", *International Journal of Operations and Production Management*, Vol.7, No.1, pp.38-49.

Gerwin, D. (1993), "Manufacturing Flexibility: A Strategic Perspective", *Management Science*, Vol. 39, No. 4, pp.395-410.

Gerwin, D. and Tarondeau, J. -C. (1989), "International Comparisons of Manufacturing Flexibility", in *Managing International Manufacturing flexibility*, K. Ferdows (ed.) (Amsterdam, North-Holland).

Gupta, D. (1993), "On Measurement and Evaluation of Manufacturing Flexibility", *International Journal of Production Research*, Vol. 31, No. 12, pp.2947-2958.

Gupta, D. and Buzacott, J. A. (1987), "Notions of Flexibility in Manufacturing Systems", Working paper, Department of Management Science, University of Waterloo.

Gupta, D. and Buzacott, J. A. (1989), "A Framework for Understanding Flexibility of Manufacturing Systems", *Journal of Manufacturing Systems*, Vol., 8, no. 2, pp. 89-97.

Gupta, Y. P. and Goyal, S. (1989), "Flexibility of Manufacturing Systems: Concepts and Measurements", *European Journal of Operational Research*, 43, pp.119-135.

Gupta, Y. P. and Goyal, S. (1992), "Flexibility Trade-offs in a Random Flexible Manufacturing System: A Simulation Study", *International Journal of Production Research*, Vol. 30, No. 3, pp.527-557.

Gupta, Y. P. and Somers, T. M. (1992), "The Measurement of Manufacturing Flexibility", *European Journal of Operational Research*, 60, pp.166-182.

Gustavsson, S. O. (1984), "Flexibility and Productivity in Complex Production Processes", *International Journal of Production Research*, Vol. 22, No. 5, pp.801-808.

Hutchinson, G. K. and Sinha, D. (1989), "Quantification of the Value of Flexibility," *Journal of manufacturing Systems*, Vol. 8, No. 1, pp. 47-56.

Hyun, J.H. and Ahn, B.H. (1992), "A Unifying Framework for Manufacturing Flexibility", *Manufacturing Review*, Vol. 5, No. 4, pp.251-260.

Jaikumar, R. (1984), "Flexible Manufacturing Systems: A Managerial Perspective", WP #1-784-078, Harvard Business School, Boston, MA.

Jaikumar, R. (1986), "Postindustrial Manufacturing", *Harvard Business Review*, Vol. 64, pp.69-76.

Jordan, W. C. and Graves, S. C. (1995), "Principles on the Benefits of Manufacturing Process Flexibility", *Management Science*, Vol. 41, No. 4, pp. 577-594.

Klahorst, H. Y. (1981), "Flexible Manufacturing Systems: Combining Elements to Lower Costs, and Flexibility", *Industrial Engineering*, Vol. 13, No. 11, pp. 112-117.

Kumar, V. (1986), "On Measurement of Flexibility in Flexible Manufacturing Systems: An Information Theoretic Approach", in *Proceedings 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, The Netherlands, pp.131-143.

Kumar, V. (1987), "Entropic Measurement of Manufacturing Flexibility", *International Journal of Production Research*, Vol. 25, No. 7, pp.957-966.

Law, A. M. (1988), "Simulation of Manufacturing Systems", *Proceedings of the 1988 Winter Simulation Conference* (eds M. Abrams, P. Haigh and J. Comfort), San Diego, CA, pp.40-51.

Lim, S. H. (1987), "Flexible Manufacturing Systems and Manufacturing Flexibility in the United Kingdom", *International Journal of Operations and Production Management*, Vol. 7, No. 6, pp. 44-54.

Mandelbaum, M. (1978), *Flexibility in Decision Making: An Exploration and Unification*, PhD thesis, Department of Industrial Engineering, University of Toronto, Canada.

Mandelbaum, M. and Brill, P. H. (1989), "Examples of Measurement of Flexibility and Adaptivity in Manufacturing Systems", *Journal of the Operational Research Society*, Vol. 40, No. 6, pp.603-609.

Mandelbaum, M. and Buzacott, J. (1986), "Flexibility and It Use: A Formal Decision Process and Manufacturing view," in *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems (Ann Arbor, MI)*, K.E. Stecke and R. Suri (Eds), Elsevier, Amsterdam, The Netherlands, pp.119-130.

Marschak, T. and Nelson, R. (1962), "Flexibility, Uncertainty and Economic Theory", *Metroeconomica*, Vol. 14, pp. 42-58.

Miller, J. G. and Roth, A. V. (1987), "Manufacturing Strategies", *Executive Summary of the 1987 North American Manufacturing Futures Survey*, Boston, MA.

Muramatsu, R., Ishii, K. and Takahashi, K. (1985), "Some Ways to Increase Flexibility in Manufacturing Systems", *International Journal of Production Research*, Vol. 23, No.4, pp.691-703.

Nagarur, N. (1992) "Some Performance Measures of Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 30, pp. 799-809.

Primrose, P. L. and Leonard, R. (1986), "Conditions under Which Flexible Manufacturing Is Financially Viable", in *Proceedings of the 3rd International*

Conference on FMS, FMS, IFS (Publications) Ltd.

Roll, Y., Karni, R., and Arzi, Y. (1992), "Measurement of Processing Flexibility in Flexible Manufacturing Cells", *Journal of Manufacturing systems*, Vol. 11, pp258-268.

Sarker, B. R., Krishnamurthy, S., and Kuthethur, S. G. (1994), " A Survey and Critical Review of Flexibility Measures in Manufacturing Systems", *Production Planning and Control*, Vol. 5, No. 6, pp. 512-523.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Sinha, D. and Wei, C. (1992), "Stochastic Analysis of Flexible Process Choices", *European Journal of Operations Research*, Vol. 60, pp. 183-199.

Silvestro, R. (1993), " The Measurement of Service Flexibility", *Proceeding of the 8th OMA Conference*, Warwick University, UK.

Slack, N. (1983), "Flexibility as a Manufacturing Objective", *International Journal of Production Management*, Vol. 3, No. 3, pp.4-13.

Slack, N. (1987), "The Flexibility of Manufacturing Systems", *International Journal of Production Management*, Vol. 7, No. 4, pp.35-45.

Slack, N. (1989), "Focus on Flexibility", in Wild, R. (Ed.), *International Handbook of Production and Operations Management*, Cassell Educational Ltd, London, pp.50-73.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advanced Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Stigler, G. (1939), "Production and Distribution in the Short Run", *Journal of Political Economy*, Vol. 47, June, pp. 305-327.

Suarez, F. F., Cusumano, M. A., and Fine, C. H. (1991), "Flexibility and Performance: A Literature Critique and Strategic Framework", Working paper #50-91 (Cambridge, MA: Sloan School of Management, MIT).

Suarez, F. F., Cusumano, M. A. and Fine, C. H. (1996), "An Empirical Study of Manufacturing Flexibility in Printed Circuit Board Assembly", *Operations Research*, Vol. 44, No. 1, January-February, pp. 223-240.

Swamidass, P. M. (1988), "Manufacturing Flexibility", Monograph No. 2, Operations Management Association.

Taymaz, E. (1989), "Types of Flexibility in a Single-Machine Production System", *International Journal of production Research*, Vol., 11, No. 11, pp1891-1899.

Upton, D. M. (1994), "The Measurement of Manufacturing Flexibility", *California Management Review*, Winter, pp.72-89.

Upton, D. M. (1995), "What Really Makes Factories Flexible?", *Harvard Business review*, July-August, pp. 74-84.

Womack, J. P., Jones, D. J., and Roos, D. (1990), *The Machine That Changed the World*, Macmillan Publishing Company.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows 2* (Special Issue on Flexible Manufacturing System), pp.143-149.

Yao, D. D. and Pei, F. F. (1990), "Flexible Parts routing in Manufacturing Systems", *IEE Transactions*, Vol. 22, pp. 48-55.

Yamashina, H., Okamura, K., and Mutsomoto, K. (1986), "Flexible Manufacturing Systems in Japan: An Overview", *Proceedings of the Fifth International Conference on flexible Manufacturing System*, November, pp405-416.

Yilmaz, O. S., and Davis, R. P. (1987), "Flexible Manufacturing Systems: Characteristics and Assessments", *Engineering Management International*, Vol. 4, No. 3, pp. 209-212.

Zelenovic, D. M. (1982), "Flexibility--A Condition for Effective Production Systems", *International Journal of Production Research*, Vol. 20, No. 3, pp.319-337

Zahran, I. M., Elmaghraby, A., and Shalaby, M. A. (1990), "Evaluation of Flexibility in Manufacturing Systems," *IEEE International Conference on System, Man and Cybernetics*, pp149-152.

Chapter 3

The Development of Flexibility Attributes

3.1 Introduction

Although manufacturing flexibility has been defined as having 11 types (Sethi and Sethi, 1990) and 3 dimensions (Slack, 1983; Gerwin, 1993) and some researchers have taken an operational viewpoint for their measurement approaches, there is still confusion and contradictions in the literature about what manufacturing flexibility is. This research argues that the reason could be that the attributes incorporated in the flexibility concept have not yet been clarified. Identifying the attributes embodied in the flexibility concept will be helpful in finding a solution to this deadlocked situation in the literature.

This thesis has so far demonstrated that the confusion existing in the literature is because researchers have proposed different explanations to express the meaning of flexibility in manufacturing systems. Following from those explanations, they have proposed different approaches to measure manufacturing flexibility. By looking into the approaches, the proposed model derives actually from part of the attributes encompassed in the flexibility. In other words, researchers have used partial attributes to explain the meaning of manufacturing flexibility, and these contradictions have resulted in different measurement approaches. Bias and other shortcomings are appearing in the proposed measurement models.

This research leads to another way of consideration to the flexibility measurement in manufacturing systems. A conceptual framework, proposed in this thesis, contains multi-attribute characteristics to depict the meaning of flexibility in manufacturing systems. Research into the measurement of manufacturing flexibility should consider all the attributes in the model; otherwise, the results of the assessment could lead to a partial solution and increase confusion. It could be that researchers have not recognized such a characteristic within the flexibility concept and this has caused the confusion concerning manufacturing flexibility measurement in the literature.

There are three categories of flexibility attributes proposed in this thesis, namely physical attributes, managerial attributes and decision attributes. The first category is divided into two sub-categories in terms of: (1) basic attributes, including efficiency and versatility, which are directly related to system effectiveness; and (2) supportive attributes, including redundancy, variety, mobility and autonomy, which will sustain the efficiency and versatility. The second category includes control and learning, which will contribute to those physical attributes. Finally, the third category is concerned with managers' decision. Two attributes fall in this category, namely weights of importance to produced tasks and probability assignment to the tasks.

It is only after the essential attributes have been identified within the concept of flexibility that the work of constructing an effective manufacturing flexibility measurement scheme can begin. Although some of the attributes have appeared in the literature, they have been individually demonstrated in the proposed approaches. Consequently, this phenomenon has led to drawbacks in the theoretical approaches to the flexibility measurement, which could be part of the cause of the confusion in the literature.

This thesis focuses on the attributes embodied in the concept of manufacturing flexibility and tries to remedy the theoretical model of measurement. To establish the flexibility measurement approaches for a manufacturing system, the question of what exactly is the meaning of flexibility in the system should be answered first. If only all factors, which affect the measurement of flexibility of a system, have been taken into account the measurement model, the work on proposing the approaches could be more possible to clarify the current confusion situation in the literature.

Following the definition of flexibility of a manufacturing system in the literature, this thesis will explore the possible factors, which are defined as attributes in the present research, of affecting it and develop a scheme for specifying the relationships between factors, which will lead to the development of a measurement approach for the study.

Theoretically, each type of manufacturing flexibility could be considered as a *system*. For a *system*, it will be able to perform a set of corespondent tasks. The tasks set contains a number of *states*. A *state* represents the outputs of the task in which the system should consume some sort of resources to produce it. Generally, the wider the range of the tasks set, the higher the flexibility is the system. This is the *versatility* attribute. Moreover, the state efficiency is measured by the usage of cost and time, comparing to the bases in theory or practice (Chang et al., 1998). It is reasonable to state that the more is the efficiency to perform the tasks set, the higher is the flexibility in the system. This is another attribute of flexibility measure -- *efficiency*. *Versatility* and *efficiency* are two basic attributes for the measurement of manufacturing flexibility.

It is also possible to argue that a system is more flexible if it is able to perform more differentiated states within the set. This depicts the *variety* attribute from the output perspective. *Variety* enforces the *efficiency* of the system. In addition, if a system wants to be flexible, not only are its subsystems required to be flexible, but also should there have *redundancy* in capability or capacity in the system to ensure that the system can perform the *states* with high *efficiency*. *Mobility* of the resources is another factor to increase *efficiency* of the system, because it facilitates the system to re-arrange the layout. *Autonomy* is important not only to the individual resource for it enables it complete tasks alone, but also to the cell level production system, in which some different resources are gathered together to build a functionally independent subsystem. An autonomous manufacturing cell can finish the assigned jobs completely with no other cell's assistance that manifests the efficient ability of the cell in one aspect, in form of reducing inter-cell movements. In all, *variety*, *redundancy*, *mobility* and *autonomy* are all supportive attributes to the efficiency and versatility of manufacturing systems.

In addition to the physical characteristics of the system, it is concerned with the aspect of management. However, it might be extremely difficult to incorporate such a consideration into the measurement model. Figure 3.1 illustrates the conceptual model of attributes scheme of flexibility in manufacturing systems. Following a description of a conventional manufacturing system, the above mentioned attributes will be explored in detail in order to sustain a theory of manufacturing system flexibility measurement.

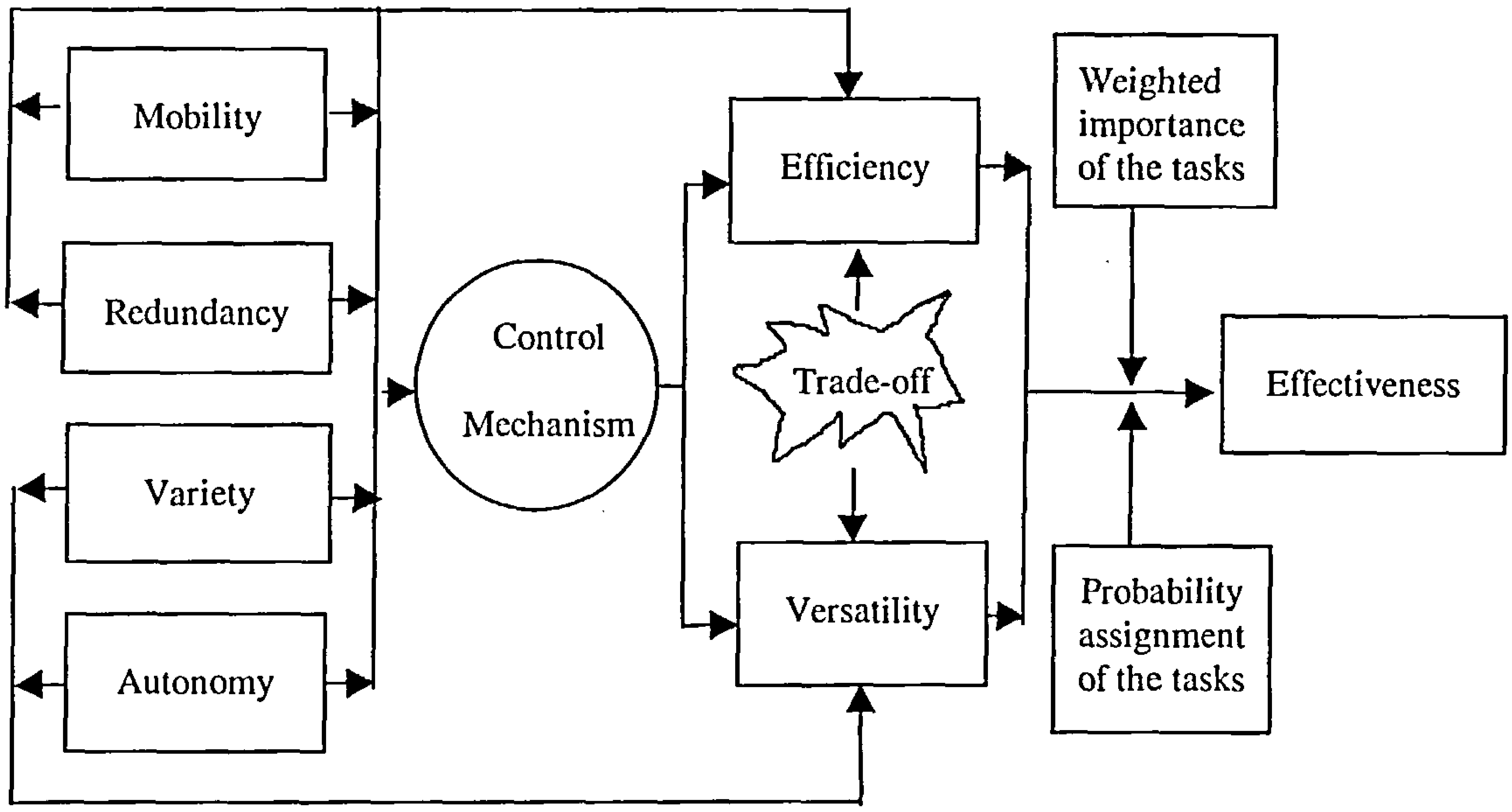


Figure 3.1: A relationship scheme of flexibility attributes

3.2 The physical characteristic attributes in flexibility

A typical form of manufacturing system defined in the present research is a plant, in which it gathers some different kinds of input resources, e.g., manpower, machines, material handling systems, buildings, materials and so froth, to construct a process or a transformation proçedure. When materials go through the process or transformation procedure, a set of tangible outputs, in terms of parts, products and/or intangible services come out from the outlay of the system, for industry or customer usage. The aspect of intangible outputs, however, is not including in this study.

Figure 3.2 illustrates a brief conventional model of a general manufacturing system with an input-process-output transformation procedure. Coupling with the transformation procedure of the manufacturing system, there are two critical performance indicators, which are always the core issues to the managers, namely effectiveness and efficiency. Effectiveness is to meet the needs from outside of the system; while efficiency is the internal requirements within the system. The former is to completely satisfy the customers' needs, and the latter fully use the resources. The conclusion is that the efficiency is to sustain the effectiveness of the system.

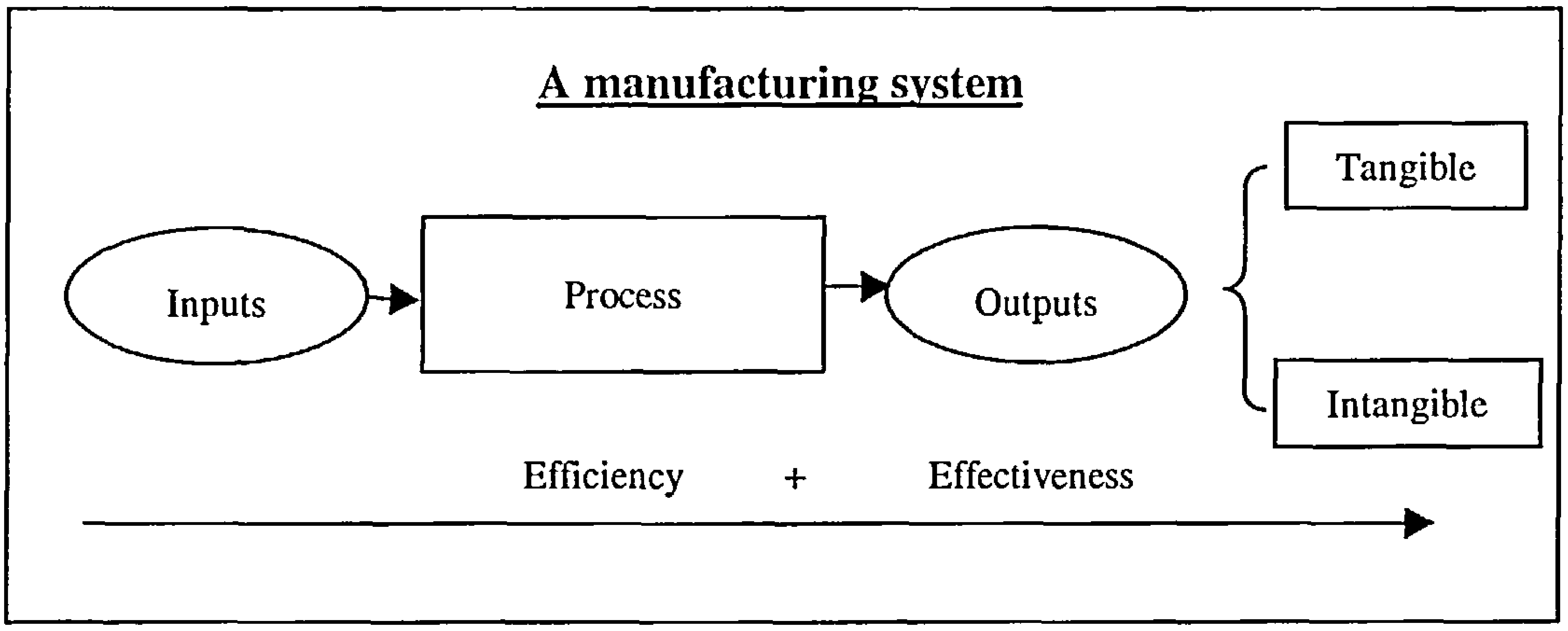


Figure 3.2: A general framework of a conventional manufacturing system

3.2.1 Manufacturing effectiveness

The effectiveness, with respect to the manufacturing flexibility, is the ability to cope with the external uncertain environments, in terms of product mix changes, fluctuation in demands and actions from competitors (Garrett, 1986; Gupta and Goyal, 1992; Zelenovic, 1982). More specifically, the effectiveness of a flexible system is the ability of closing the gaps between customers' needs and the capabilities of a company and hence increases its performance.

It could be sensible to explain that effectiveness of a firm is associated with its competitive advantage in the marketplaces. If the evolution of the competitive advantages can be traced as: cost in the era of 30's, quality in the 50's, flexibility in the 80's, and time in the 90's, the current demands of the consumers appear to be satisfaction with low cost, high quality, a wide range of alternative products and quick service. It is therefore very important to conclude that low price, which is based on the *economies of scale* to gain cost edge, is no longer the only way to compete in the marketplace, but also high quality, wide variety of products and short lead times. Cost-efficiency is insufficient the only factor of achieving effectiveness. The efficiency factors here for the effectiveness of a manufacturing system should be extended to have more additional considerations.

Efficiency of performing the tasks is not only for sustaining external effectiveness, but also internal effectiveness. The exhibition of internal effectiveness is to neutralize internal disturbances, in terms of equipment breakdown, variable task time, queuing delays, reworks and rejects, etc. (Buzacott and Mandelbaum, 1985). The ability demonstrated in sustaining internal effectiveness is by means of excess capacity and capability, in forms of redundant machines to reroute the production process or redundant manpower to deal with such unexpected disturbances.

3.2.2 Basic attributes

3.2.2.1 Efficiency

The efficiency has been always the major concern in the management of a manufacturing system and its value, which has been used in very broad concept and hence interpreted in many ways, is expressed by the performance of the objectives, when compared with the set of bases. The measurement of efficiency of a system is quite flexible in that it depends upon the chosen factors and the decided comparison basis. It is possible to add or substitute some of the factors or change the bases in the efficiency measurement models to fit the circumstances of the system. The general approach could be expressed by comparing output to input, output to output or input to input for any chosen parameters.

In the conventional production management era, the efficiency was achieved by mass production, stable production line, long production run for one setup of production process and produce one type of product. The *economy of scale* is the main strategy for the competitiveness. The cost-efficiency is the main indicator of production performance. Productivity, normally expressed by outputs divided by inputs, and has been a popular approach to measure the efficiency of a system, in which the input factors are generally associated with the consideration of cost.

Buzacott (1982) demonstrated an efficiency ratio, which is to compare the expected production rate taken with the disturbances from machine failures to the expected production rate without them, to depict the flexibility of a machine. The flexibility measurement suggested by Buzacott (1982) is actually an efficiency consideration only and an output-orientated comparison.

The approach proposed by Son and Park (1987) is a cost-based efficiency measurement approach. They adopted the measure of dividing total output by the cost factors, in terms of idle cost, waiting cost, setup cost and inventory cost to measure equipment flexibility, process flexibility, product flexibility and volume flexibility respectively. Obviously, Son and Park (1987)'s approach is merely cost-efficiency consideration as a measure of flexibility measurement.

However, the production theory based on cost-efficiency orientation is not sufficiently able to cope with the fluctuations and changes in the marketplaces, during the 1980s and even further in the 1990s. As stated above, to sustain the effectiveness of the system, it is necessary to consider efficiency factors in more detail. Slack (1989) pointed that measuring flexibility of a manufacturing system time is more important than cost. Moreover, it has been recognized that time is emerging as the next competitive advantage (Stalk and Hout, 1988).

Brill and Mandelbaum (1989) measured the efficiency of a system by doing a set of tasks and comparing them with the reference set of tasks used in industry. Their chosen factor is only determined by the relative time to complete an operation including setup time. They further stated that the approach could be expanded to include output quality, throughput, reliability, and maintenance costs, etc. Setup time or changeover time, which has been suggested by many researchers in the literature as a factor to measure flexibility of a system (Barad and Sipper, 1990; Upton, 1994), is actually a time-based consideration. In addition, versatility element to the flexibility measurement, Barad and Sipper (1990) adopted setup time in their Petri-Nets measurement approach, which demonstrating a time-based efficiency measurement approach.

This thesis suggests that there is a need to separate the efficiency factor into dynamic efficiency and static efficiency. Dynamic efficiency depicts the capability of changeover among the states, while static efficiency depicts the ability of performing the states., It shows in the literature that dynamic efficiency seems more attractive to researchers than that of static efficiency. This thesis stresses that static efficiency is an essential element needed to understand the concept of flexibility. This is the reason that flexibility embodies dynamic and static attribute in the concept itself (Tidd, 1991).

Researchers, (Slack, 1989; Barad and Sipper, 1988) thought that trade-off between cost and time is possible. However, time is more important than that of cost in flexibility perspective. Gupta and Goyal (1989) said that the use of advanced equipment to perform the tasks is always more expensive than that of functional resources, but consumes less time. This is the example they use to depict the trade-off of time with cost. Nevertheless, researchers argued that to use simple and non-expensive facilities are also able to demonstrate the same flexibility level of the system, if only the system can make great efforts on management, e.g., setup time reduction (Schomberger, 1986; Shingo, 1985). This means that flexibility is not always expensive. This is also part of the reason that this thesis addresses flexibility embodied management attributes, which will be explored latter.

This thesis is, therefore, not suggesting that cost can be substituted by time entirely, rather these two factors are able to combine together to depict the efficiency and for sustaining the effectiveness of the system. Chung and Chen (1990)'s measurement can be a supportive approach to such a viewpoint. The approach of cost and time combined in the efficiency measurement, proposed by Chang et al. (1998), appeared to be a more reasonable proposition. However, it seems that it is not yet a practical consideration, since firms are entering a complicated and turbulent environment in the current marketplace.

The competitive edge has been changed into the era of *economies of scope* (Goldhar and Jelnek, 1983). A manufacturing system in the current competition environment is imperative to have the efficient ability to produce a variety of products for the customers. Moreover, since customers need more than cost, quality and variety of products only, they would like to pay more to have the products quicker that makes time as coming up the new edge in the 90's.

The author proposes that in the near future the competitive edge could be characterized as the era of *economies of space*, which means that worldwide companies all over the world will be able to achieve economic effects of production. Due to the rapid improvements in the development and application of computer and telecommunication, the emerging trend of global development is producing a virtual organization, in which the abilities to produce the products are coming from outside of the companies. The competitive advantage appears to be the interconnection with other companies those who are having their own core competencies, no matter where the companies are located.

For dealing with such an emerging complicated situation for sustaining the effectiveness of a system, the consideration of efficiency assessment of a system requires a more comprehensive model. The Data Envelopment Analysis (DEA) approach (This will be explored in detail in the next Chapter) could be a promisingly suitable method for measuring such a complicated efficiency element (Chang et al., 1998).

3.2.2.2 Versatility

Versatility is defined in this research as a set of output tasks produced by a system or subsystem. This is the same as Brill and Mandelbaum (1989)'s definition of 'system task set' and similar to Slack (1989)'s explanation about the flexibility dimension of range, the envelope of the states. Generally, the more the number of tasks in the specific set for the system, the more flexible is the system. Tincknell and Radciffe (1996) defined versatility, with more specification, as 'the ability of a system to change intentionally in standard ways.'

Versatility is almost the synonym of flexibility in many research reports (Chatterjee et al., 1984; Browne et al., 1984; Jaikumar, 1986; Sethi and Sethi, 1990). They simply counted the number of tasks produced within the output set of the system. Barad and Sipper (1990) argued that Chatterjee et al. (1984)'s definition of measuring manufacturing flexibility did not consider the efficiency of the machine with respect to the various operations. The approaches with respect to a theoretical measurement of versatility, which have appeared in the literature, are referring to Kumar (1986, 1988), Yao (1986). However, Chandra and Tombak (1992) and Chang et al. (1998) argued that the entropy approach also lacks efficiency consideration. Versatility is an essential element in the concept of flexibility, but not the only one.

Expanded from a single machine flexibility measurement, Mandelbaum and Brill (1989) proposed the group machine flexibility measurement as the function of (1) machine-task effectiveness (efficiency of doing the tasks), (2) tasks weighted importance, (3) probabilities of doing the tasks, and (4) the number of tasks in the task set, under the conditions of (1) task set to be assigned, and (2) machine group being evaluated.

The approach proposed by Mandelbaum and Brill (1989) for a single machine flexibility measurement is to sum up the weighted efficiencies of doing the assigned tasks. Taking the same approach, they measured the group machine flexibility, on the one hand, with an optimistic perspective, by summing up the selected maximum value of efficiency for each task. Then with a pessimistic perspective, they chose the minimum value of efficiency for each task. A Hurwitz measure is used for taking a convex combination of the maximum and minimum criteria with respect to the tasks. For generalization, they suggested a probabilistic measure of machine-group flexibility approach and treated the optimistic and pessimistic and the Hurwitz measures are special cases of the probabilistic measure.

It is intuitive that the maximum, minimum and Hurwitz measures not only lack a versatility factor, but also a lack of redundancy (This will be explained in detail in the next section) by taking only the maximum and/or minimum efficiency value of the task, when measuring the group-machine flexibility. The probabilistic measure seems a more sensible concept, because it takes the versatility factor into the model, where the group-machine flexibility increases with increase of the number of tasks. However, there is still a lack of redundancy consideration, because it confines each task to a probability distribution assignment to the candidate machines. The restriction of such an assignment will not guarantee increase of candidate machines leading to increase flexibility value. Consequently, Mandelbaum and Brill (1989) stated a flexibility-dominated machine may exist in a group of machines, if the group-machine flexibility is not affected by removing the machine.

Nevertheless, adding a machine means increasing the excess of capacity or capability for the system (Slack, 1989). It should, therefore, increase the group-machine flexibility. Such a conclusion has been demonstrated in Figure 3.3, as long as there is redundancy in the system. Figure 3.3, 1 represents that the machine is capable to perform the corespondent part. This also can be proved by the entropy approach (Kumar, 1986, 1987). Brill and Mandelbaum (1989) also specified the redundancy property of increasing flexibility of the group machine with an increasing number of machines in the group.

However, the approach proposed by Brill and Mandelbaum (1989) explained the flexibility properties in one aspect, in terms of redundancy, but not in all aspects. Their work omitted versatility. **The increase with the number of machines in a machine group is not equal to increase with the number of parts produced by the machine group, if the added machines are all redundant ones**, showing in Figure 3 from case 1 to case 2.

$$\begin{array}{c|cc} & M_1 & M_2 \\ \hline P_1 & 1 & 1 \\ P_2 & 1 & 1 \end{array}$$

Case 1: Original matrix

$$\begin{array}{c|cccc} & M_1 & M_2 & M_3 & M_4 \\ \hline P_1 & 1 & 1 & 1 & 1 \\ P_2 & 1 & 1 & 1 & 1 \end{array}$$

Case 2: Two redundant machines added to original matrix

Figure 3.3: Adding redundant machines to the system

Barad (1992) adopted Brill and Mandelbaum (1989)'s viewpoint and proposed the versatility measurement of a system as the sum of the versatilities of all machines in the system. Barad also valued the versatility of a machine with Chatterjee et al. (1984)'s approach, in which a machine's versatility is measured by 'the expected fraction of operations that the machine is capable of performing.' As mentioned above, Barad (1992)'s approach has the same drawback as Brill and Mandelbaum (1989).

3.2.2.3 Efficiency and versatility

Traditionally managers believe that there exists a trade-off between efficiency and versatility, a form of flexibility.

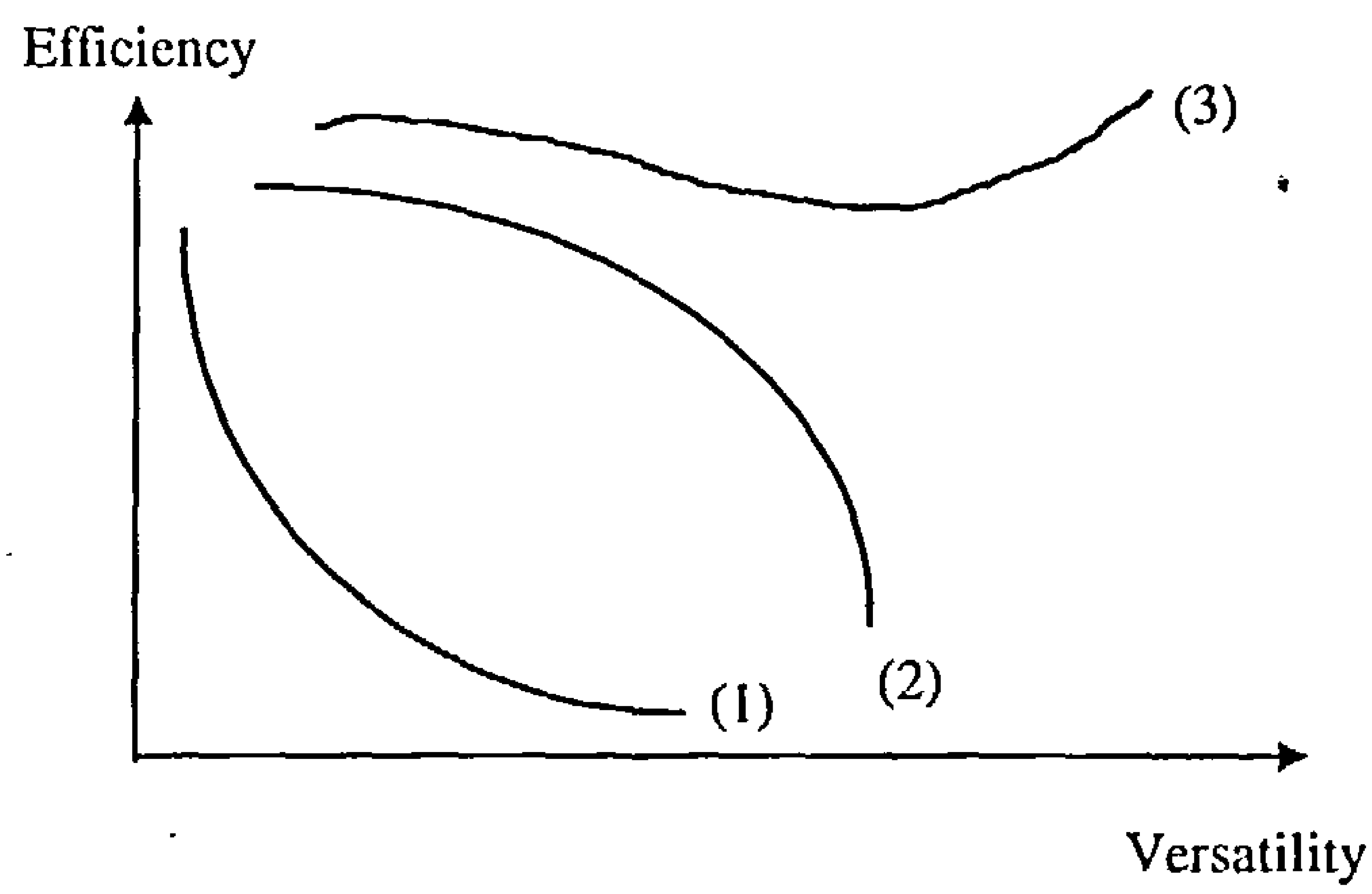


Figure 3.4: The relationship between efficiency and versatility

In Figure 3.4, curve (1), (2) and (3) represent the relationship between efficiency and versatility with short-term, mid-term, and long-term respectively. In the short-term, increase versatility the system likely reduces its efficiency dramatically, due to accommodating the system into the new circumstances, e.g., setup a machine for producing a new part or introducing a new product into the production system. In the mid-term, when a system has learned how to reconcile the new situations, the efficiency could be increased mildly. Finally, for a good system, the efficiency value should be increased as well as versatility. These conclusions are similar to Gustavsson (1984)'s observations.

The conclusion is that as long as the system has the ability to learn to neutralize the disturbances from introducing new tasks into the system, efficiency and versatility can go hand by hand. This accords with Slack (1989)'s viewpoint that there will be no trade-off between cost-efficiency and flexibility in 1985-1995. The ability to cope with the trade-offs has been increased by applying advanced manufacturing technology in one way; while the other way should be by management, for instance, an effective control system, in terms of automatic control and intelligence contról (Tincknell and Radcliffe, 1996), or in practice, an another instance, which is a way of learning and continuous improvement in Japanese companies.

Versatility is a demonstration of the physical characteristics. Efficiency is not completely depicted by the same characteristics, but it is also concerned with the control mechanism of the system. **Certainly, a system's flexibility partly comes from its physical components - subsystems, and partly from the system's controllability -**

integration, coordination and cooperation. The former contributes to the system flexibility by its own versatility and efficiency; while the latter contributes by increasing the efficiency of the system.

3.2.3 Supportive attributes

3.2.3.1 Redundancy

Slack (1989, 1991) proposed that flexibility implied some sort of redundancy, and the redundancy includes three forms of excess in terms of capacity, capability and utilization. Although Slack mentioned that it is worth developing, researchers do not seem to be paying enough attention to this aspect. Correa (1994) echoed the same viewpoint and pointed out that managers seem to prefer the concept of a reserve potential to refer the flexibility of a system. Gerwin (1993)'s viewpoint of 'banking' is similar to redundancy, which is an investment for future alternatives. Hall and Tonkin (1990) stated that Japanese companies plan for this in terms of extra facilities, computer systems and capable manpower to fit the needs of future competition.

Redundancy is necessary to complete the tasks smoothly, when mal-functions occurred, in terms of tools break, machine breakdown or labour absenteeism, etc., in the system. In other words, **redundancy of resources in a way is to sustain the efficiency of a system.** For a further examination on the concept of redundancy in the attribute of flexibility, two cases are demonstrated in Figure 3.5.

$$\begin{array}{c} \\ P_1 \\ P_2 \end{array}\begin{array}{cc} M_1 & M_2 \\ \multicolumn{2}{c}{\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}} \end{array}$$

Case 1: Two machines produce two parts

$$\begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \\ P_4 \end{array}\begin{array}{cc} M_1 & M_2 \\ \multicolumn{2}{c}{\begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}} \end{array}$$

Case 2: Two machines produce four parts

Figure 3.5: Two simple extreme cases

Suppose that there are two machines M_1 and M_2 in a system and both of them can process two parts. Here are two extreme cases, which might be of interest to identify the group machine flexibility of the system. In the matrix of the cases, 1 represents the correspondent machine is able to process the part with the efficiency of 1, while 0 is not applicable for the operation to the corespondent machine.

The two cases show that M_1 and M_2 have the same flexibility, if we, for simplicity, assign the efficiency of the operations all as 1. However, it might be of interest in grouping the two machines together and to identify the group machine flexibility of two cases. It could be said that Case 2 is more flexible than Case 1 as it can produce 4 different parts, while Case 1 just two. As mentioned above, researchers agreed that a more flexible system is able to produce a wider range of products. The number of outputs is proposed as an indicator of flexibility measurement. This exhibits another attribute of flexibility - *versatility.* However, Case 1 shows that M_1 is able to substitute M_2 when M_2 is breakdown, indicating that Case 1 is embodied more operation flexibility and Case 2 is none. A flexible system is that of containing the ability to cope with the uncertain environment. Machine breakdown is one of the internal environmental uncertainties. Therefore, there is a need of having redundant machines for the 'in case' occurred. Which one of the two cases is more flexible from the aggregate point of view?

Figure 3.5 demonstrated that, although rather simple of the cases, it is helpful to clarify the attributes of the flexibility concept. For Case 1, on the one hand, the system is capable of coping with endogenous disturbances, the failures of the system, since the system has dynamic flexibility, in which one of the machine is breakdown, the other one can be of supplement. Case 1 exhibits a form of redundancy. On the other hand, Case 2 shows that the system can produce more versatile products for the customers, meaning that the system has more ability of coping with exogenous disturbances, depicting that the system embodies more static flexibility. It therefore demonstrates that the system of Case 2 has more versatility.

In summary, Figure 3.5 indicates that the measurement of a grouped resources flexibility requires to consider another important attribute embodied in the flexibility concept - redundancy - in addition to the measurement elements of a single resource flexibility, versatility and efficiency, proposed by Chang et al. (1998).

It is interesting to examine the flexibility measurement approach in the surveyed literature with the attributes developed in this thesis so far. Kumar (1986, 1987)'s entropy approach for measuring operation flexibility of a system is likely more related to measuring versatility and redundancy, although it has a drawback of lacking efficiency consideration (Chang et al., 1998; Gupta and Goyal, 1989). The increase of the number of redundant machines for processing one operation and the increase of the number of operations that the system can perform contribute the value of entropy evaluation of the system. However, such a conclusion is not able to explain the case 2 in Figure 3.5. It may encounter a phenomenon called "**the flexibility paradox of grouping resources**", **which means the increase of the number of flexible machines will not be necessarily increasing the flexibility of the system**, if they all have no redundant abilities, because the entropy value of case 2 in Figure 3.5 is nil.

On the contrary, there is another interesting example, a number of dedicated machines grouped together could generate a flexible system. It can be seen in Figure 3.6. Comparing the phenomena of these two cases, it shows that the case in Figure 3.6 is more reasonable than that of the Case 2 in Figure 3.5 and hence supporting that the redundancy attribute is an important factor in measuring flexibility of a system. Gupta (1993) committed such a comment in his observation that '**high degrees of flexibility can be achieved by combinations of quite inflexible equipment.**' Redundancy is in one aspect; moreover, versatility is in another aspect.

$$\begin{array}{c c} & \begin{array}{cccc} M_1 & M_2 & M_2 & M_3 \end{array} \\ \begin{array}{c} P_1 \\ P_2 \end{array} & \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \end{array}$$

Figure 3.6: A flexible system with dedicated machines

3.2.3.2 Variety

Variety is defined as the difference among the tasks of output within a specific system. Generally, the more the differences are, the higher the degree of versatility and hence the higher degree of the flexibility.

It is reasonable to state that system A is more flexible than B, if two systems are individually able to produce two products P_1 and P_2, however, system A can produce two entirely different products P_1 and P_2; while system B produces the two products with some degree of commonality. The result shows that the variety factor is another essential factor in measuring system flexibility even in the single resource flexibility as well as in the flexibility at group level (Gupta, 1993).

It is therefore necessary to distinguish the difference among the output tasks of the system for explaining the meaning of flexibility in the manufacturing system. Gupta (1993) expanded the viewpoint from Collier (1981) and Easterfield (1964). The measurement of variety at least includes three factors, namely the number of products in the product set produced by the system, the degree of component commonality and the degree of processing commonality. The first factor stated by Gupta (1993) is actually the same as versatility measurement. The research in this thesis therefore argues that variety measurement is the inverse of commonality, in terms of components and/or processing, among the output task set. It seems to be sensible to conclude that variety enhances versatility to a certain extent and shows a more efficient system from the output viewpoint.

Das (1996) proposed that it is necessary to consider the difference between all routes for producing a part or product, when measuring routing flexibility. Das suggested that the difference measurement should include: (1) the requirement of material control, (2) processing time, (3) processing operations, (4) processing machines, and (5) production quality. The point of view is consistent with Gupta (1993). Moreover, Das (1996) pointed that it is also necessary to measure the difference between all products that produced by the process when measuring the process flexibility. The difference between all products should include: (1) product handling procedure, (2) the operations to be performed, (3) the processing time, (4) the necessary processing skills, and (5) the physical differences between the products.

Chang et al. (1998) proposed a revised entropy approach for measuring a single resource, taking the example of a machine, with two factors in terms of efficiency and versatility to measure the flexibility of a machine. There is, however, a need to have further consideration of variety from the output perspective. The reason that Chang et al. (1998) did not take the variety measurement into account, because it might be not meaningful at a single resource level, is because it seems hard to distinguish the degree of difference between two operations. The operations themselves are all stand alone. However, when the resources have been grouped together, they integrate the operations to get the ability to produce a certain range of parts or products. It could be more meaningful to distinguish the degree of difference between two parts or products, because they contain integration and synergy, not just technology elements, but management in the system.

In the measurement model, variety can be considered as a weighted factor like the weighted importance of the tasks (Brill and Bandelbaum, 1989). However, there is no need to sum the weighted vectors up to 1, as it appears that having more tasks in the set does not necessarily increase the value of system flexibility.

3.2.3.3 Mobility

Mobility defined in this research is as the ability to move resources. Machine mobility means to move the machines in the plant or even in different sites of the plants, when they are needed. The needs of moving the resources are due to the changes of products or parts or the changes of production methods or processes. The ability to change the layout of the plant is another form of flexibility, namely layout flexibility. The Japanese companies show more flexibility than that of Western companies. This is partly due to the mobility of the resources in the plants. One way of changing the position of the machines is to add wheels under the machines. It could therefore be easy to move a machine by a few operators in a few minutes.

Layout flexibility seems important to a flexible system for introducing the new products, changing product mix or production volume. However, the literature does not seem to be paying attention to such an area. **Re-layout of the plant can reach and maintain the optimum condition of production, as long as movements of the facilities in the plant can be easily done.** For instance, if there is a machine breakdown, which will make the system re-route the production procedure and keep the production function running smoothly, the system needs redundant machines. Nevertheless, if the redundant machines are hard to move, chaos arises in the system consequently due to the long distance movement of the parts. It will increase the complexity of transportation of material or work-in-progress. Suppose that there is a movable redundant machine, the production functions can be simply replaced and the route will not be changed.

Upton (1994) defined mobility as in a broader way, involving changeover times. This can mean different "time aspects" in different production system levels. At the machine level, it means operations setup, while process setup is for producing the different products or parts. However, such changeovers in terms of time and cost have been included in the efficiency factor proposed in this thesis.

Efficiency defined in the research of this thesis involves two aspects, namely dynamic efficiency and static efficiency, which gives flexibility dynamic and static properties. Dynamic efficiency refers to the effectiveness of making the changes, while static efficiency involves processing the changes. Therefore, the mobility defined in this research is a rather narrow aspect in the concept, which is a supportive factor to efficiency, but a rather important factor for adjusting the plant layout.

It has been proved that the Toyota Production System (TPS) is more flexible than that of the Ford Production System (FPS) (Womack et al., 1990). The method of coping with the volume fluctuation of the TPS is to change the operators in the production line, which demonstrates the mobility of manpower, a form of the adjustment of production capacity. Following the same idea, if the machines can be moved, it is another way of changing capacity. Not only can it reduce the movement distances of raw material and work-in-progress, but also the inventory levels. The result is sequentially improving the production efficiency at the system level.

One of the reasons that man is more flexible than machine is inherently the mobility in the human being. Another factor of making man more flexible is versatility, which comes from the learning ability, for new things, skills, knowledge, technologies, and so forth. However, man is not as efficiently as machine, because a machine can do some particular things quicker and more economic than an operator. That is one of the reasons why the owners intend to replace operators with machines, especially automatic equipment. Nevertheless, a machine is still less flexible than man in terms of versatility. The scientists, mechanical engineers, industrial engineers are all making an attempt to put intelligence into the machines to make them have the learning ability and then the mobility to make them more autonomous, meaning that they can finish the assigned tasks on their own, with no support from man.

It is not only necessary for a single resource to have mobility, but also a set of combined different kinds of resources, a manufacturing cell, or even plant as a whole. Hall and Tonkin (1990) observed that Japanese companies design manufacturing facilities to incorporate the ability to transform their individual production system for changing circumstances in the next century. **There is an emerging trend that a global manufacturing system is becoming a core issue in the international manufacturing strategy. The manufacturing mobility, in forms of production technologies, new products, or manufacturing processes, appears to be an essential factor to compete in the current manufacturing environment. It shows the importance of mobility at cell level or system level.**

3.2.3.4 Autonomy

A resource or a set of combination of resources within a production system that is able to produce a set of tasks without any other assistance is called autonomy. Some advanced manufacturing technology equipment, for example, which are designed to perform a variety of products alone show more flexibility than that of multi-functional machining centers which need operators to supervise or to do some supportive activities.

Autonomy is an important factor of constructing a focused factory. The concept of 'plant within a plant' (PWP) is to separate existing facilities into several organizational and physically independent divisions for focusing specific tasks (Skinner, 1974). By breaking the large production line into some small functionally independent production units, the company can increase flexibility, improve quality, and shorten the manufacturing lead time, and embodies the ability to cope with demand fluctuations by changing the number of workers.

Autonomy is a major way to form a new system in the current manufacturing environment. An automation factory is a typical example. Managers and engineers are all aiming at constructing a completely automatic flexible manufacturing system. However, in many cases, it shows that they still need some manual assistance to smooth the production line, even in a so-called automatic factory. Such supportive activities obviously have a negative effect on system efficiency, because it takes times, occupies more resources and thus increasing operation costs.

An operator can be considered as a flexible worker, provided he/she can finish a range of different operations alone. If only he/she finishes those jobs with other worker's help, his/her demonstration on efficiency decreases in some degree and hence it reduces his/her flexibility.

With the direction of future development in production management, the generic factory could be a good coherent example to describe the autonomy attribute. Building the success of Group Technology (GT), a small self contained and self managed organizational structure is likely to win in a highly dynamic and structurally complicated environment. A whole factory contains a number of such kind of small groups of entities. The entities all have self-analogous and self-organized characteristic and are all able to be connected to each other by well constructed information network to form a highly efficient information communication system. Moreover, each entity has its own dynamic development ability to generate a dynamic structure and accommodate the disturbances caused by internal and external environments. The generic factory is a highly flexible organizational structure; however, such an organization should be coupled with the managerial aspect of organizational culture development, which will be discussed later.

3.3 Managerial attributes

Gupta and Buzacott (1989) noted that there is no one-to-one relationship between system flexibility with its physical components. It is therefore insufficient to consider the flexibility measurement in manufacturing system simply with the physical characteristics. They addressed that the control mechanism, at least, plays an important role. Nevertheless, the assessment of manufacturing flexibility with managerial factors is extremely difficult. Even though, it is at least an essential factor to the aspect of improving it.

The works performed by a system do not actually reflect the flexibility of the system. The flexibility of a manufacturing system is somewhat related to its potential (Slack, 1983; Gerwin, 1993; Upton, 1995). Although the potential of the system could be a more important aspect than that of its actual works in reflecting flexibility, when it encounters unexpected changes, it is obviously difficult to quantify the potential of the system. However, it is possible to create potential, provided there is a learning and control scheme for the system. The scheme is not just for the human being, but also for hardware facilities of the system.

3.3.1 Control

Flexibility measurement cannot just be considered within a static domain, in which the set of output tasks has been specified, including its output task range and changeover times and task costs. A system, which runs in such a certain environment, should be called a versatile system not a flexible system. A flexible system has the ability to explore the unknown and unpredictable situations, encompassing the uncertainties of the environment.

The physical characteristics are not able to explain the entire concept of manufacturing flexibility. A manufacturing system consists of a number of different resources within a certain area and produces a set of particular outputs. It seems unreasonable to sum the physical characteristics of the resources or entities individually as the flexibility of the whole system. Barad (1992) determined that the system versatility is to sum the versatility of all machines in the system. This seems a simplistic approach, which will be demonstrated in Chapter 5.

The flexibility in concept is implicitly including the ability of coping or adjusting itself to the new circumstances. The new circumstances of a system may be internal or external disturbances. Those disturbances are so complicated that they could not be solved by an individual resource. The solution needs integration, coordination and cooperation to elaborate synergies. Parts of the synergies are generated by control. Kikert (1985) stated the importance of control for flexibility as follows:

Flexibility is a method for increasing the control ability of the system, particularly for generating control capacity in case of unexpected disturbances. Flexibility is a form of metacontrol. It is not just the application of some control measures from an existing arsenal: it has to do with an increase in control capacity, with an extension of the exiting arsenal of control measures -- in short, with improvement in the controller itself, which is, by definition, a form of metacontrol.

3.3.2 Learning

Learning to do new tasks and do them efficiently is the way to a flexible system. If a system has no ability to learn new things from outside the system, it will fade out quickly. A flexible system cannot exhibit the ability to perform versatile tasks efficiently only. Its outcome is just confined to a particular domain. Tincknell and Radcliffe (1996) called it a versatile system rather than flexible system, because a versatile system can be reached by automatic control; while flexible system requires intelligent control. A flexible system calls for the ability to do something new for any new situation. To do something new depends on the ability to learn. Learning, therefore, is more concerned with expanding the domain of the outcome. In other words, learning will improve the capacity and capability of the system.

Tinknell and Radcliffe (1996) defined a flexible system concerned with learning as a system which is able to learn by increasing the versatility of the system. More generally, it is required to improve the attributes embodied in the concept of flexibility, e.g., they need to learn how to improve their operation efficiency; versatile abilities; the variety in outputs; and their mobility. Learn to reduce setup times for improving the effective changeover. One aspect of efficiency, is the way of Toyota Production System achieve system flexibility. To find out how to expand an operator's ability of performing different operations is to improves their versatility and allows redundancy in the system and is capable of coping with volume fluctuations.

It is rather difficult to explain how to incorporate learning into a manufacturing system other than a human being. Kolb (1984) proposed a model of experimental learning, which stated that the learning should be expanded from experience. A process of 'abstract conceptualization' is useful for understanding the way of learning. Tincknell and Radcliffe (1996) contributed a learning cycle approach in which new responses might be adopted by modifying existing responses, generated in the previous experiences of flexible actions from automatic control, or by intelligent control to generate a non-standard response, which needs to use the capabilities of the system. Kikert (1985) demonstrated a "metalevel" of learning concept to improve flexibility. That is metalearning, 'the learning of learning behavior, the learning to learn', represented by 'deuterolearning'.

Therefore, the "learning to learn" more efficient ways with versatile standard responses and/or non-standard approaches could increase flexibility of a system.

The learning ability for a manufacturing system comes from many ways. It starts mainly from a motivation of learning from their manpower. It is an important issue for managers to construct an atmosphere of learning in the organization. Learning, for example, is the way of leading to continuous improvement for Japanese companies. Involving with job rotations in the daily operations, Japanese employers are not only expanding their capabilities, but also overlapping their abilities, which demonstrates the redundancy attribute, in the form of excess capability with manpower. Moreover, through learning they are capable of improving their dynamic efficiency in terms of reducing setup times on changing parts or products production, which is really the aim of a flexible system.

3.4 Decision attributes

Weighted importance of tasks has been considered as one of the factors that will affect flexibility measurement in its evaluation model (Mandelbaum and Brill, 1989). Such an assignment will deviate among different system levels. At the machine level, for example, managers may decide which parts could be essential to the system or to be assigned to a particular machine. Even though a machine is potentially able to produce a variety of types of part, it is likely to be shown as a dedicated machine in practice. If the machine is mostly confined to producing a few types of part, dedication follows. While, at the plant level, it relates to which product mix should be introduced into their market segments to gain the maximum profit, which volumes are more profitable to the system, and which new products will be more attractive to customers. These are related to the managers' decision-making.

Such kind of a decision making will reduce the degree of freedom in exhibiting its flexibility. Potential flexibility and actual flexibility, addressed by Gerwin (1993), need to be distinguished. It is therefore necessary to examine the factors that affect the difference.

A likelihood matrix for the machines to perform the output tasks set, which was proposed by Mandelbaum and Brill (1989), could be considered to be a factor of assignment generated by the customer or a trend of market change. These will affect a company's objectives.

3.5 Concluding remarks

The flexibility of a manufacturing system is not simply to sum up the flexibility of its physical components, because the versatility of the system does not equal the summation of system components' versatility and similarly the efficiency of the system is not likely to be the sum of the efficiency of its physical components.

The concept of flexibility in manufacturing is so complicated that it can not be easily treated with part attributes. The confusion and contradictions arise in the conclusions from the measurement models. For the sake of understanding the flexibility better in the manufacturing system and clarifying the confusions and contradictories in the literature, it is imperative to have an in depth exploration into the attributes of flexibility. This may be the contribution of the present research in the thesis to the literature.

The research into flexibility attribute is a new direction added to the current literature. The attributes embodied in the concept of flexibility in manufacturing systems have been classified and clarified. Ten attributes have been proposed in this thesis. However, different attributes could be chosen having different levels of system flexibility or different flexibility type. The conceptual framework of attributes in flexibility proposed in this research could be used to do further theoretical and empirical tests.

3.6 References

Barad, M. (1992), "Impact of Some Flexibility Factors in FMSs -- A Performance Evaluation Approach", *International Journal of Production Research*, Vol. 30, No. 11, pp.2587-2602.

Barad, M. and Sipper, D. (1988), "Flexibility in Manufacturing System: Definition and Petri Nets Modeling", *International Journal of Production Research*, Vol. 26, No. 2, pp.237-248.

Barad, M. and Sipper, D. (1990), "Flexibility and Types of Changes in FMSs: A Timed Petri-nets Assessment of Machine Flexibility", *The International Journal of Advanced Manufacturing Technology*, 5, pp.292-306.

Brill, P. H., and Mandelbaum, M. (1989), "On Measurement in Manufacturing Systems", *International Journal of Production Research*, Vol. 27, No. 5, pp.747-756.

Brill,P. H. and Mandelbaum, M. (1990), "Measurement of Adaptivity and Flexibility in Production Systems", *European Journal of Operational Research*, 49, pp.325-332.

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P. and Stecke, K.E. (1984), "Classification of Flexible Manufacturing System", *The FMS Magazine*, 2 (2), pp.114-117.

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the 1st International Conference on FMSs*, Brighton, UK, pp.13-22.

Buzacott, J. and Mandelbaum, M. (1985), "Flexibility and Productivity in Manufacturing Systems", in *Proceedings of the IIE Conference*, (Chicago, IL), Industrial Engineering and Management Press, Atlanta, CCA, pp.404-413.

Chang, A.Y., Whitehouse, D. J., Chang, S. L.and Hsieh, Y. C. "A Revised Entropy Approach to the Measurement of Manufacturing System Flexibility", in *Proceeding of the Joint Conference of The Fifth International Conference on Automation Technology (Automation 98') and 1998 International Conference of Production Research (Asia Meeting)*, 20-22 July, 1998, Taipei, Taiwan, R.O.C.

Chatterjee, A., Cohen, M. A., Maxwell, W. L. and Miller, L. W. (1984), "Manufacturing Flexibility: Models and Measurements", in *Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.49-64.

Chen, I. J., Calantone, R. J. and Chung, C. H. (1992), "The Marketing-Manufacturing Interface and Manufacturing Flexibility. *OMEGA*, 20 (4), pp.114-117.

Chung, C. H. and Chen, I. J. (1990), "Managing the Flexibility of Flexible manufacturing Systems for Competitive edge", in M. J. Liberatore (Ed.), *Selection and Evaluation of Advanced Manufacturing Technologies*, Springer-Verlag, New York, pp.280-305.

Collier, D. A. (1981), "The Measurement and Operating Benefits of Component Part Commonality", *Decision Science*, 12, pp85-96.

Correa, H. L. (1994), *Linking Flexibility, Uncertainty and Variability in Manufacturing Systems*, Avebury, Ashgate Publishing Limited, England.

Cox, J. T. (1989), "Toward the Measurement of Manufacturing Flexibility", *Production and Inventory Management Journal*, First Quarter, pp.68-72.

Das, S. K. (1996), "The Measurement of Flexibility in Manufacturing Systems", *The International Journal of Flexible Manufacturing Systems*, 8, pp.67-93.

Easterfield, T. E. (1964), "Optimum Variety", *Operational Research Quarterly*, 15, pp.71-85.

Ettile, J. E. (1988), "Implementation Strategies for Discrete Parts Manufacturing Technologies: Final NSF Report", University of Michigan (Ann Arbor, MI: University of Michigan).

Garrett, S. E. (1986), "Strategy First: A Case in FMS Justification", in, *Proceedings of the 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.17-30.

Gerwin, D. (1993), "Manufacturing Flexibility: A Strategic Perspective", *Management Science*, Vol. 39, No. 4, pp.395-410.

Goldhar, J. D. and Jelinek, M. (1983), "Plan for Economies of Scope", *Harvard Business Review*, Nov.-Dec., pp.88-94.

Gupta, D. (1993), "On Measurement and Evaluation of Manufacturing Flexibility"," *International Journal of Production Research*, Vol. 31, No. 12, pp.2947-2958.

Gupta, Y. P. and Goyal, S. (1989), "Flexibility of Manufacturing Systems: Concepts and Measurements", *European Journal of Operational Research*, 43, pp.119-135.

Gupta, Y. P. and Goyal, S. (1992), "Flexibility Trade-offs in a Random Flexible Manufacturing System: A Simulation Study", *International Journal of Production Research*, 30, pp.527-557.

Gupta, Y. P. and Somers, T. M. (1992), "The Measurement of Manufacturing Flexibility", *European Journal of Operational Research*, 60, pp.166-182.

Gupta, Y. P., Gupta, M. C. and Narang, S. (1989), "Flexible Manufacturing Systems. Flexibility and Availability: An Information Theory Approach", Working Paper, School of Business, University of Louisville, KY.

Gustavsson, S. O. (1984), "Flexibility and Productivity in Complex Production Processes", *International Journal of Production Research*, Vol. 22, No. 5, pp.801-808.

Hall, R. and Tonkin, L. (Eds.) (1990), *Manufacturing 21 Report: The Future of Japanese Manufacturing, Association for Manufacturing Excellence*, Wheeling, IL.

Hyun, J.H. and Ahn, B.H. (1992), "A Unifying Framework for Manufacturing Flexibility", *Manufacturing Review*, Vol. 5, No. 4, pp.251-260.

Jaikumar, R. (1986), "Postindustrial Manufacturing", *Harvard Business Review*, Vol. 64, pp.69-76.

Kickert, W. J. (1985), "The Magic Word Flexibility", *International Studies of Management and Organization*, Vol.14, No.4, pp.6-13.

Kolb, D. A. (1984), *Experiential Learning* (Englewood Cliffs, NJ: Prentice-Hall).

Kumar, V. (1986), "On Measurement of Flexibility in Flexible Manufacturing Systems: An Information Theoretic Approach", in *Proceedings 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, The Netherlands, pp.131-143.

Kumar, V. (1987), "Entropic Measurement of Manufacturing Flexibility", *International Journal of Production Research*, Vol. 25, No. 7, pp.957-966.

Mandelbaum, M. and Brill, P. H. (1989), "Examples of Measurement of Flexibility and Adaptivity in Manufacturing Systems", *Journal of the Operational Research Society*, Vol. 40, No. 6, pp.603-609.

Mandelbaum, M. and Buzacott, J. (1990), "Flexibility and Decision Making", *European Journal of Operational Research*, 44, pp.17-27.

Miller, J. G. and Roth, A. V. (1987), "Manufacturing Strategies", Executive Summary of the 1987 North American Manufacturing Futures Survey, Boston, MA.

Ramasesh, R. V. and Jayakumar, M. D. (1991), "Measurement of Manufacturing Flexibility: A Value Base Approach", *Journal of Operations Management*, Vol. 10, NO. 4, pp.446-468.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Schomberger, R. J. (1986), World Class Manufacturing - The Lesson of Simplicity Applied, The Free Press.

Shingo, S. (1985), *A Revolution in Manufacturing: The SMED System*, Productivity Press.

Skinner, W. (1974), "The focused factory", *Harvard Business Review*, May-June, p.113-121.

Slack, N. (1983), "Flexibility as a Manufacturing Objective", *International Journal of Production Management*, Vol. 3, No. 3, pp.4-13.

Slack, N. (1987), "The Flexibility of Manufacturing Systems", *International Journal of Production Management*, Vol. 7, No. 4, pp.35-45.

Slack, N. (1989), "Focus on Flexibility", in Wild, R. (Ed.), *International Handbook of Production and Operations Management*, Cassell Educational Ltd, London, pp.50-73.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advance Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Stalk, G. J. and Hout, T. H. (1988), "Time - The Next Source of Competitive Advantage", *Harvard Business Review*, July/August.

Swamidass, P. M. (1985), "Manufacturing Flexibility: Strategic Issues", Discussion Paper 305, Graduate School of Business, Indiana University, IN.

Swamidass, P.M. and Newell, W.T. (1987), "Manufacturing Strategy, Environmental Uncertainty and Performance: A Path Analytic Model", *Management Science*, Vol. 33, No. 4, pp.509-524.

Tidd, J. (1991), *Flexible Manufacturing Technologies and International Competitiveness*, London: Printer Publishers.

Tincknell, D. J. and Radcliffe, D. F. (1996), "A Generic Model of manufacturing Flexibility Based on System Control Hierarchies", *International Journal of Production Research*, Vol. 34, No. 1, pp.19-32.

Upton, D. M. (1994), "The Measurement of Manufacturing Flexibility", *California Management Review*, Winter, pp.72-89.

Womack, J. P., Jones, D. J. and Roos, D. (1990), *The Machine That Changed the World*, Macmillan Publishing Company.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows* 2 (Special Issue on Flexible Manufacturing System), pp.143-149.

Zelenovic, D. M. (1982), "Flexibility--A Condition for Effective Production Systems", *International Journal of Production Research*, Vol. 20, No. 3, pp.319-337

Chapter 4

A Development of the Flexibility Attributes Measurement Models

4.1 Introduction

Excellent work has been done in building the groundwork for a better understanding of manufacturing flexibility by Gerwin (1982), Buzacott (1982), Brown et al. (1984), Jaikumar (1986), Slack (1983, 1987), Gupta and Goyal (1989), Sethi and Sethi (1990), Hyun and Ahn (1992) and Gerwin (1993). Their works include explorations into flexibility typologies, dimensions, time frames, measurement approaches, among others. Those efforts have contributed to an important step in providing practice for industry and understanding for academic researchers. However, Sethi and Sethi (1990), Ramasesh and Jayakumar (1991) and Gerwin (1993) argued that too little work has been done to explore analytical models in operational applications.

The work in this field still lacks a unified framework for defining and evaluating manufacturing systems flexibility (Benjaafar et al., 1995). Researchers (Gupta and Goyal, 1989; Ramasesh and Jayakumar, 1991; Gupta, 1993), have doubted the possibility of achieving such a goal. It does not seem sensible to propose a unified flexibility measurement approach for each flexibility type. The work in this thesis has revealed that different types of flexibility actually encompass different types of attributes inside the concept. It is not the intention of this thesis to propose a unified framework for the manufacturing flexibility measurement, rather it is hoped that it will be a step towards that goal.

This thesis suggests a different way of thinking on manufacturing flexibility research, especially for operational applications. Without suitable implementation in the work place, it will be difficult to establish flexibility as an important competitive edge in strategic practice. With the flexibility attributes developed in Chapter 3, some operational related research on proposed measurement models, which have been examined by this thesis, show partial attributes characteristics. It is obvious that this is the wrong measurement. Manufacturing flexibility cannot just consider partial attributes. This could also be the reason why researchers in this field have argued that the flexibility of a manufacturing system is complicated and difficult to quantify (Gupta and Buzacott, 1989; Upton, 1995).

The main purpose of this chapter is to propose measurement models for the flexibility attributes developed in the last chapter. This chapter begins with an examination of the measurement models in the literature from the operational perspective and relates them to the flexibility attributes in Section 2. Section 3 introduces an input/output table for the description of a general manufacturing system. Given the table, the attributes of different measurement models could be established. From Section 4 to 11 are the models established for efficiency, versatility, redundancy, variety, mobility, autonomy, the occurrence of probability and the "weights of importance measurement" respectively. Section 12 concludes with some findings and contributions in this research.

4.2 Literature review

With respect to more effective management in the manufacturing systems, the research in the field of manufacturing flexibility has been divided into three levels namely the strategic level, the tactical level and the operational level (Hyun and Ahn, 1992). The strategic level is concerned with how to adapt flexibility to cope with environmental changes. The tactical level pays attentions to the relationship between flexibility and the performance of a manufacturing system; whereas the operational level focuses on how to construct a model to measure the flexibility of a system. A survey in the literature revealed that little work has been done to develop the measurement models at operational levels (Sethi and Sethi, 1990; Ramasesh and Jayakumar, 1991). The work in this thesis contributes to the operational level.

In the operational level of manufacturing flexibility, researchers have concentrated on model based applications. The researchers related to this level include Barad and Sipper (1988, 1990), Benjaafar and Talavage (1992a, 1992b), Brill and Mandelbaum (1989), Mandelbaum and Brill (1989), Buzacott (1982), Chang et al. (1998), Chatterjee et al. (1984), Chung and Chen (1989, 1990, 1996), Das (1996), Graves (1988), Gustavsson (1984), Kumar (1986, 1987), Son and Park (1987) and Yao (1985).

The difficulties of proposing a single measure of flexibility stressed by Gupta and Buzacott (1989) is associated with two problems: (1) the difficulty of considering physical properties and control mechanisms in the flexibility measurement model simultaneously, and (2) the difficulty of comparing two flexible systems, if they are characterized by different requirements such as producing a wide range of products or the ease of switching between different products. It certainly is difficult to distinguish the interaction between physical properties and the control mechanism adopted by managers and to construct a scheme for measuring the control mechanism, as it is just like quantifying the concept of management and proposing a measurement model for it. However, this measurement problem could be overcome by constructing performance-oriented criteria. The difficulty addressed in (2) above has been characterized as versatility and efficiency attributes in this research and measurement models have been constructed for them.

It can be recognized that the concept of flexibility in a manufacturing system is actually characterized by multi, complex and contradictory factors. It is therefore necessary to distinguish the profound characteristics embodied in the flexibility concept, treat them separately first, and then try to combine them together with different attributes for the measurement of flexibility at different system levels and for the measurement of different types of flexibility.

An effort has been made to examine some suggested measurement approaches which have appeared in the literature with the attributes developed in the present research, as illustrated in Table 4.1. It examines the consistency of those measurement approaches and the attributes, rather than exactly the same mathematical models.

Atkinson's (1985) measurement was focused on labour flexibility measurement. His proposal of the number of workers ready to change each other, the number of different types of tasks performed by the workers, the ease of changing compensation schemes as the measurement of numerical flexibility, fundamental flexibility and financial flexibility are depicted by redundancy, versatility and efficiency attributes respectively.

Buzacott's (1982) viewpoint is of a general efficiency concept in nature, a measure of deficiency of the system when doing changeovers. In addition, Buzacott's (1982) job flexibility, which measured the ratio of the number of part types that could be processed by the system to the total number of the parts set, represents versatility measurement.

Table 4.1: A review of the suggested measurement approaches in the literature associated with the flexibility attribute

Attributes / Reports	Efficiency			Versatility	Redundancy	Variety	Mobility	Autonomy	Weight	Probability
	Cost-based	Time-based	General							
Atkinson (1985)		✓		✓	✓					
Barad and Sipper (1988,1990)		✓		✓						
Brill and Mandelbaum (1989)		✓							✓	✓
Browne et al. (1984)	✓		✓	✓						
Buzacott (1982)			✓	✓						
Carter (1986)	✓	✓		✓						
Chandra and Tomback (1992)		✓		✓						
Chang et al. (1998)	✓	✓		✓						
Chatterjee et al. (1984)				✓	✓					
Chung and Chen (1989)				✓						
Chung and Chen (1990)	✓	✓							✓	
Chung and Chen (1996)			✓		✓					
Das (1996)		✓		✓		✓			✓	
Falkner (1986)		✓								
Gerwin (1993)	✓	✓		✓						
Gupta (1993)						✓				
Kumar (1986, 1987)				✓	✓					
Mandelbaum and Brill (1989)			✓						✓	✓
Primerose and Leonard (1986)					✓					
Sethi and Sethi (1990)	✓			✓	✓					
Slack (1983)	✓	✓		✓						
Son and Park (1987)	✓									
Upton (1995)		✓		✓			✓			
Yao (1985)				✓						

Browne et al.'s (1984) suggestions mostly concerned efficiency and versatility attributes. In their research, routing flexibility was measured by the cost of production lost on rescheduling jobs. Expansion flexibility was measured by the ease of adding capacity. Product flexibility was measured by the time or cost usage for changing from one product to another. And, volume flexibility was measured by the smallest volumes to be produced by the system profitably. These suggestions all belong to efficiency attribute considerations. They also measured process flexibility by the number of different part types produced by the system, which belongs to the versatility attribute.

The entropy approach, which has been applied to flexibility measurement models in the literature, actually involves two attributes, namely versatility and redundancy. Kumar (1986, 1987) included both of them; however, Upton (1995) applied it as the former and Yao (1985) the latter.

The Petri-Nets approach, which was applied by Barad and Sipper (1988, 1990) for flexibility measurement, includes a setup time element, a time-based consideration, and versatility attribute in their models.

Slack (1983), Carter (1986) and Gerwin (1993) suggested that the measurement of manufacturing flexibility should consider three dimensions, namely cost, time and range. Such a suggestion obviously takes into account both efficiency, the cost-based and time-based orientation, and versatility attributes.

Son and Park (1987) proposed to measure equipment flexibility, process flexibility, product flexibility and volume flexibility with idle cost, waiting cost, setup cost and inventory cost to divide the total output respectively. Their proposal is actually the cost efficiency concept in nature. Whereas, Falkner's (1986) suggestion was focused on the time aspect considerations, in which he measured machine flexibility by the ratio of setup time to processing time and indicated throughput and machine downtime hours as routing and operation flexibility.

Chung and Chen (1990) measured the total system flexibility with two factors, namely the quickness of response to a change and economic response to the change, meaning the time and cost efficiency concepts. Expanding from such a method, Chang et al. (1998) proposed a revised entropy approach to add to the versatility consideration of the flexibility measurement model.

Brill and Mandelbaum (1989) and Mandelbaum and Brill (1989) proposed to sum up the weighted importance of effectiveness of doing a set of production tasks. Such an approach considered the attributes of general efficiency and task importance weights. Further, they suggested a probability distribution assignment to the set of tasks to estimate the expectation of the tasks occurrences for measuring the effectiveness of coping with the changes of environment. Chung and Chen (1996) followed their method to measure machine flexibility; moreover, they measured routing flexibility by the redundancy attribute.

Normally researchers have measured routing flexibility with the concept similar to the number alternative options for choice (Chatterjee et al., 1984; Yao, 1985; Kumar, 1986, 1987; Chung and Chen, 1989). That is the application of the redundancy attribute. Primerose and Leonard's (1986) proposal, the ratio of actual paths to the ideal paths of the system as the measure of routing flexibility, followed the same idea.

Chatterjee et al.'s (1984) suggestion of the counting of options for the measurement of routing flexibility and process flexibility belong to the redundancy attribute consideration. They use the ratio of available paths to the total paths in a system as the measure of material handling flexibility, which was the versatility measurement application. Moreover, they measured machine flexibility as the expected fraction of operations within the total operations set performed by the system that the machine is capable of performing. This also appears to be a work as a versatility attribute.

Gupta (1993) mentioned that it is vitally important to consider the difference between the set of tasks, meaning the variety consideration. Das (1996) summarized some researchers' (Brill and Mandelbaum, 1989; Gupta, 1993; among others) ideas for the proposal of his measurement approaches. Therefore his measures have broader considerations.

Taking the cost of switching from one operation to another as a measurement of machine flexibility, as proposed by Sethi and Sethi (1990), is the cost-efficiency attribute; using the number of different process plans for a part to measure operation flexibility is a redundancy attribute consideration; while taking the range of volume of all part types that the system can run profitably as the measurement of volume flexibility is the versatility attribute.

In all, in Table 4.1, it can be seen that the issues of mobility and autonomy seem not yet to have been received attention from the researchers. Rather they have been more interested in only the efficiency, versatility and redundancy attributes. This thesis argues that the proposal for the measurement of manufacturing flexibility should at least take into account the attributes suggested here in the present research.

4.3 A general input/output table

It should be noted that the concept of flexibility of a manufacturing system is actually characterized by three aspects in terms of input, process and output. At first, people see the flexibility of a manufacturing system from the output perspective. That means a flexible system is the system which is able to accommodate itself to the changing environment. The evidence of such ability is the production of a wide range of variant products at any customized volume. Explicitly, the ability is supported by the input resources, the functions they put in, and its process, the way they organize, integrate and manage their resources.

The ability to produce various products requires flexible input resources. Moreover, the system should have the ability to arrange or rearrange those resources in flexible ways to form different processes and procedures and to perform a set of operations for producing the products. The assessment of the flexibility of a manufacturing system has to take into account these three aspects. With such a consideration, it can be seen that there are relationships between the attributes and these three aspects in the following explorations. A simple input/output table of a manufacturing system can help to make clearer the development of an attributes measurement approach.

Figure 4.1 represents a general framework for the development of the measurement models in this thesis.

		Outputs			
		T_1	T_2	$\cdots$	T_n
Inputs	S_1	O_{11}	O_{12}	$\cdots$	O_{1n}
	S_2	O_{21}	O_{22}	$\cdots$	O_{2n}
	$\vdots$	$\vdots$	$\vdots$	O_{ij}	$\vdots$
	S_m	O_{m1}	O_{m2}	$\cdots$	O_{mn}

Figure 4.1: A general input/output table of a manufacturing system

In Figure 4.1, S_i represents a set of input resources i, a combination of different kinds of facilities and/or workforce in the system, where $i=1,...,m$ and m is the number of sets of the resources, which are all able to produce a set of outputs, T_js. The S can mean different objectives when measuring at different system levels, e.g., an operator, a machine, a group of operators, a group of machines, a manufacturing process, a manufacturing cell or even a plant.

The T_js represent the set of the output tasks, where $j=1,...,n$ and n is the number of the tasks produced by the system. The T can also mean different things at different system levels, e.g., the operation of a single machine, a part in a group of machines, a product in a manufacturing cell or a plant, etc. The variables need to be specified correspondingly, when measuring flexibility at different system levels or with different flexibility types.

The O_{ij} represents the ability of the resource i to produce the task j, meaning a set of output performance factors, e.g., production cost, throughput rate, production lead time, changeover time, production volume, output quality, etc.

4.4 The development of efficiency measurement

Although a flexible system must have an ability to produce versatile outputs, fundamentally, efficiency remains a necessary requirement for a manufacturing system, as it has become a qualifying criterion in the competitive marketplace in the 1950s (Chang, 1999). Moreover, a versatile system is not necessarily the same as a flexible system. At least, the latter incorporates the efficiency element itself. Therefore, a flexible system is not only able to produce a wide range of output set, but also to produce them at high efficiency. The evaluation of the efficiency attribute is consequently the first factor in developing the flexibility measurement model. Once the work on the efficiency factor has been evaluated, the evaluation of the other attributes can be carried out.

Eilon (1985) suggested four production efficiencies, namely technical efficiency, cost efficiency, capacity utilization and revenue efficiency, which could be measured by comparing maximum output and minimum input with actual input or output to evaluate the system performance. He further stated that '*there are obviously numerous performance ratios that can be defined, depending on which inputs and outputs are selected for analysis*'.

4.4.1 Measurement bases

The measurement of efficiency of a system could be either an absolute value, or a relative value. It depends upon the basis of comparison with a reference set. Firstly, if it is compared with the theoretical value, it results in an absolute value of efficiency, whereas when it is compared with the other values, e.g., the peer group in the practice or the standard basis built in the firm, it will be a relative value of efficiency. The former implies potentially possible levels of reference. It indicates a measure of potential efficiency, a greater space for improvement in practice.

The second case, as described by Farrell (1957) is concerned more with the observed standard than the theoretical one.

...Although there are many possibilities, two at once suggest themselves -- a theoretical function specified by engineers and an empirical function based on the best results observed in practice. The former would be a very natural concept to choose -- after all, should not a postulated standard of perfect efficiency represent the best that is theoretically obtainable? Certainly, it is a concept used by engineers themselves when they discuss the efficiency of a machine or process. However, although it is a reasonable and perhaps the best concept for the efficiency of a single production process, there are considerable objections to its application to anything so complex as a typical manufacturing firm, let alone an industry.

Following Farrel's (1957) approach, Charnes et al. (1978) developed data envelopment analysis (DEA), which will be applied later in this research, as a methodology to evaluate the relative efficiency of decision-making units (DMUs) on the basis of observed performance in the peer group. Such a measure of efficiency is the concept of benchmarking. Flexibility is one of manufacturing strategy's priorities. It would be suitable for a manufacturing system to adopt the best practice in the industrial peer group.

Finally, in a plant, by involving synthetic and statistical techniques, industrial engineers establish the specific standards for the required input for each kind of output. Golany and Roll (1992) proposed that such a consideration could be added to the DEA model. It could be a simpler way to use their own established standards, set up by industrial engineers for their own company, as the measurement basis instead of comparing with the peer group in industry.

Therefore, this thesis suggests that there are, at least, three types of bases for the measurement in terms of theoretical bases, the best practice bases and standard bases. With three bases, it is possible to define the necessary improvement and the potential improvement for the system. Such a consideration is consistent with Gerwin's (1993) viewpoint of actual flexibility, required flexibility and potential flexibility. The efficiency concepts shown in Figure 4.2 could be considered as the source of a flexibility viewpoint derived from Gerwin (1993).

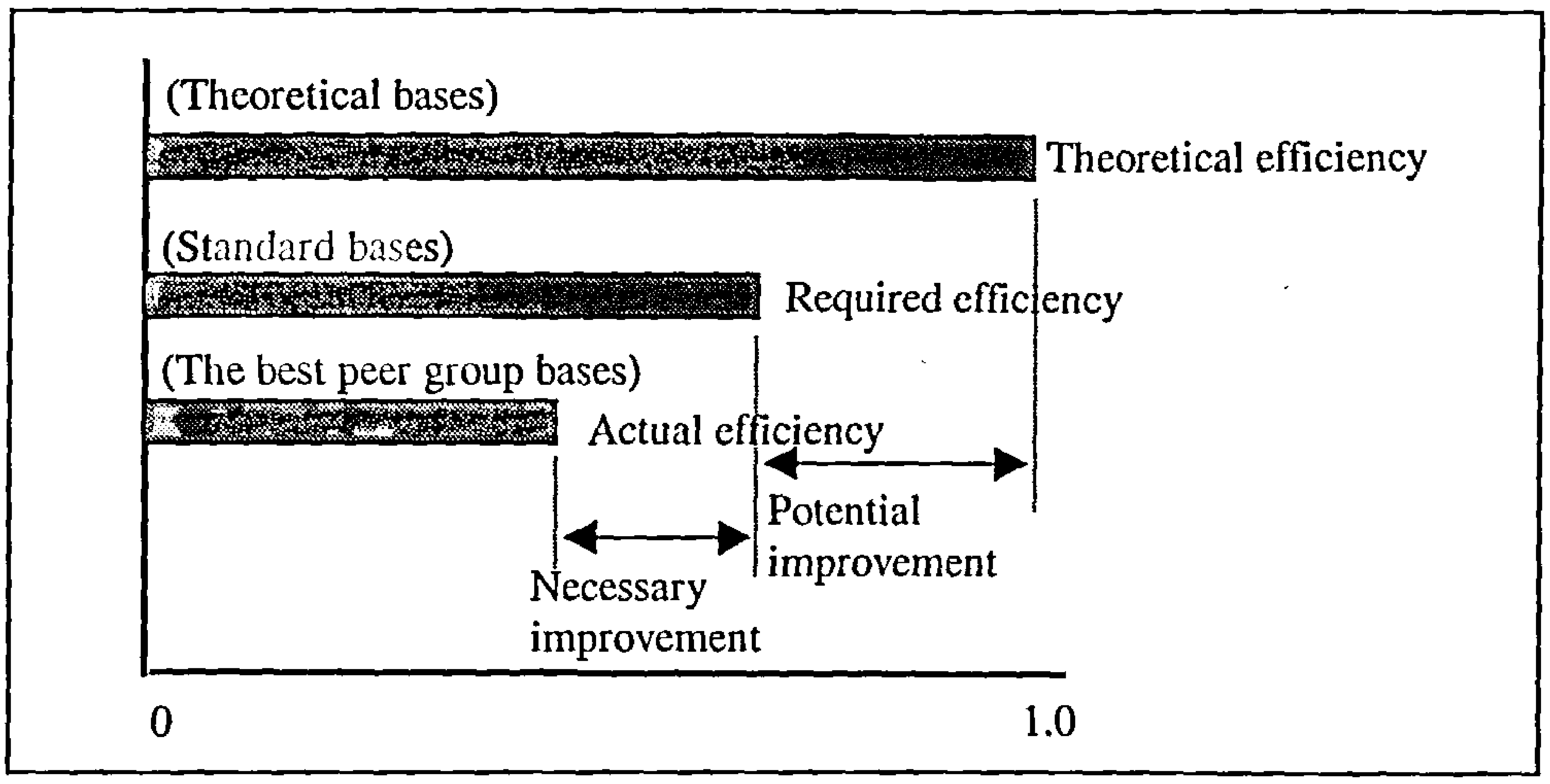


Figure 4.2: Efficiency levels of a system

4.4.2 An efficiency development framework

Efficiency measurement as proposed in this research considers time and cost factors simultanously. It therefore incorporates time-based and cost-based efficiency measurement. The measurement could also be divided into dynamic and static efficiency, if the time and cost factors are divided into changeover elements and processing elements. The structure can be illustrated as Figure 4.3.

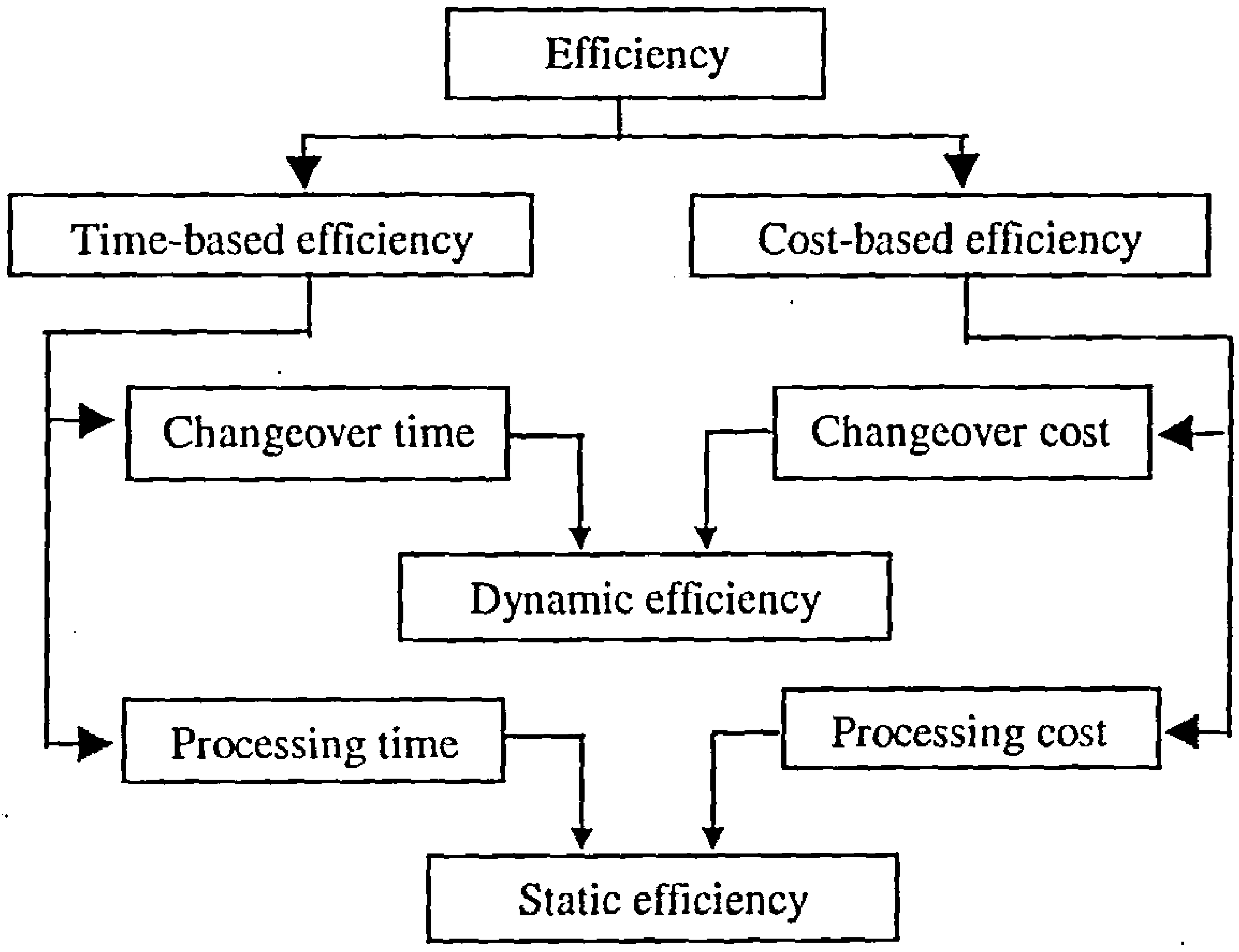


Figure 4.3: An efficiency framework with flexibility measurement

4.4.3 Measurement factors development

In practice, it is easier for a company to take cost as the efficiency evaluation basis than time, because managers track production costs all the time. Consequently, in theory, researchers, such as Son and Park (1987), have proposed cost orientation as a measurement criteria. Son and Park (1987) proposed flexibility measurement as being the same concept as productivity. They measured equipment flexibility, process flexibility, product flexibility and volume flexibility with idle cost, waiting cost, setup cost and inventory cost to divide the total output respectively. The method proposed by Son and Park (1987) is actually related to efficiency measurement with a cost aspect, i.e., cost-based efficiency consideration, rather than considering flexibility measurement from the viewpoint of this research, which it is argued in more comprehensive.

Slack (1989) stated that the ease of making the changes from one state to the other involves not just cost but also time. In most cases, time and cost have their trade-off and time might be more important than cost. Upton (1994) adopted changeover time as a factor of manufacturing flexibility, which was defined as mobility, which is actually a time-based consideration. Barad and Sipper (1988, 1990) suggested setup time as the element in their Petri-Net model, which is also an example of a time-based orientation.

This thesis suggests that the evaluation of manufacturing system efficiency should be depicted in terms of both time and cost. Chung and Chen (1990) proposed the same viewpoint when they examined the total system flexibility (*TSF*) with two conceptual schemes, which embodied the quickness of response to a change (*Q*) and economic response to the change (E), i.e., time and cost dimensions. The two conceptual schemes are:

$$(a) TSF = \alpha Q + (1-\alpha)E \text{, where, } 0 \leq \alpha \leq 1 \tag{4.1}$$

$$(b) TSF = Q^{\alpha} E^{\beta} \text{, where } \alpha+\beta=c \text{ and } c \geq 1 \text{ is a constant} \tag{4.2}$$

Although the two schemes proposed by Chung and Chen (1990) have their drawback in rating the manufacturing flexibility, as stated by Chang et al. (1998), their approach actually depicts the evaluation of efficiency. This thesis has adopted formula (4.2) as the measurement approach. Therefore, an operation function (OI_{ij}) has been defined as the product of operation time (T_{ij}) and operation cost (C_{ij}), indicating the ability of resource i to produce the output task j.

$$OI_{ij} = (T_{ij})^{a}(C_{ij})^{b} \tag{4.3}$$

where a, b are constant, $a+b = c$, and $c \geq 1$ for the more generalized consideration. The operation funtion (OI_{ij}) is therefore a major factor in the assessment of efficiency of resource i in performing task j. The value of efficiency should compare the actual values of time and cost spent on the activities by the system to the measurement bases, namely theoretical basis, standard basis or the best practice in the peer group, which the system takes.

However, researchers and managers might be further interested in looking into how to set the factors embodied in the OI_{ij}, if they are concerned that time is more important than cost as the competitive criterion, or in a more dynamic aspect than a static one. Following from such a consideration, the research in this thesis develops in detail the division of the productive function into cost-based and time-based efficiency factors. Furthermore, this research divides the operation factors into dynamic and static elements, namely changeover and processing elements. Consequently, it is possible to explore the work on cost- or time-based flexibility measurement and dynamic or static flexibility measurement.

4.4.3.1 Cost-based efficiency factors development

Cost has always been the major concern of performance for the managers of a firm. They consequently adopt cost as the measurement factor of the effectiveness of running a business, as it is directly related to the profit of the firm. Hence, the cost accounting system is established as the control tool. It is therefore quite easy for managers to use the cost factor as the efficiency measurement.

The cost assessment of producing a task, denoted as the operation cost, includes the setup for the production of the task when it is idle or doing another task and the process of the task. Thus, the operation cost (C_{ij}) of resource i at producing task j includes changeover cost (C_{ij}^{s}) and processing cost (C_{ij}^{p}).

$$C_{ij} = C_{ij}^{s} + C_{ij}^{p} \qquad (4.4)$$

(1) Changeover cost

Changeover cost is defined as the cost of setup of a system for performing a task. The setup on a machine, e.g., includes the change of tools, fixture, jigs etc. for producing different types of parts or performing different operations. Equation (4.5) illustrates a transition cost matrix of a resource i from changing the production task r to s.

$$C_{ir,is}^{s} = \left[c_{ir,is}^{s}\right] = \begin{bmatrix} c_{i1,i1}^{s} & c_{i1,i2}^{s} & \cdots & c_{i1,in}^{s} \\ c_{i2,i1}^{s} & c_{i2,i2}^{s} & \cdots & c_{i2,in}^{s} \\ \vdots & \vdots & \cdots & \vdots \\ c_{in,i1}^{s} & c_{in,i2}^{s} & \cdots & c_{in,in}^{s} \end{bmatrix} \tag{4.5}$$

where $c_{ir,is}^{s}=0$, when $r=s$, where $r=1,...,n$, $s=1,...,n$. $c_{ir,is}^{s}$ represents the changeover cost of resource i from changing the production task r to s. It is not necessarily equal to $c_{is,ir}^{s}$, because the changing process is not necessary equally reversible. $C_{ir,is}^{s}$ is therefore a cost-based transition matrix.

Derived from the cost transition matrix (4.5), the changeover cost to produce task j on resource i is taken as the mean value of the transition from the other tasks to the task j.

$$C_{ij}^{s} = \frac{1}{n(n-1)}\sum_{r=1}^{n} c_{ir,ij}^{s} \tag{4.6}$$

Therefore, the total changeover costs for producing all the tasks on resource i is illustrated as (4.7).

$$TC_{ij}^{s} = \left[C_{ij}^{s}\right] = \left[C_{i1}^{s} \quad C_{i2}^{s} \quad \cdots \quad C_{in}^{s}\right] \tag{4.7}$$

(2) Processing cost

Processing cost is defined as the cost of finishing an operation on a part or product. The total processing costs for producing all the tasks on resource *i* is demonstrated as (4.8).

$$TC_{ij}^{p} = \left[C_{ij}^{p}\right] = \left[C_{i1}^{p} \quad C_{i2}^{p} \quad \cdots \quad C_{in}^{p}\right] \tag{4.8}$$

where $j=1,\ldots,n$. n is the number of tasks that the system is able to produce. The C_{ij}^{p} represents the processing cost of state j on resource i. Therefore, the operation cost C_{ij} could be expressed by (4.9).

$$C_{ij} = C_{ij}^{s} + C_{ij}^{p} \tag{4.9}$$

4.4.3.2 Time-based efficiency factors development

Time is emerging as the key factor of competitive advantage to a firm in the turbulent marketplace (Stalk and Hout, 1988). Managers are increasingly paying more attention to time than cost. One of the reasons is that time is an easier concept than other indicators, like gross margin and market share, for workers to understand. It is therefore easier for a firm to implement time as the performance evaluation factor in the daily operational work.

The measurement of operation time (T_{ij}), like the measurement of cost, includes changeover time (T_{ij}^{s}) and processing time (T_{ij}^{p}).

$$T_{ij} = T_{ij}^{s} + T_{ij}^{p} \tag{4.10}$$

(1) Changeover time

In a similar way to the concept of changeover cost, changeover time is defined as the time required for the preparation of the next process. Equation (4.11) illustrates a transition time matrix of resource i in changing the production task r to s.

$$T_{ir,is}^{s} = \left[t_{ir,is}^{s}\right] = \begin{bmatrix} t_{i1i1}^{s} & t_{i1i2}^{s} & \cdots & t_{i1in}^{s} \\ t_{i2i1}^{s} & t_{i2i2}^{s} & \cdots & t_{i2in}^{s} \\ \vdots & \vdots & \cdots & \vdots \\ t_{ini1}^{s} & t_{ini2}^{s} & \cdots & t_{inin}^{s} \end{bmatrix} \tag{4.11}$$

where $t_{ir,is}^{s}$ =0, when $r=s$, where $r=1,\ldots,n$, $s=1,\ldots,n$.

$t_{ir,is}^{s}$ represents the changeover time from task r to s on resource i and also is not necessarily equal to $t_{is,ir}^{s}$. T_{ij}^{s} is therefore a time-based transition matrix of resource i when changing the production among tasks js, where $j=1,\ldots,m$.

The changeover time (T_{ij}^{s}), illustrated in equation (4.12) and represented as the time required for the preparations needed to perform task j on resource i, also takes the mean value changeover times from processing the other tasks to task j.

$$T_{ij}^{s} = \frac{1}{n(n-1)} \sum_{r=1}^{n} t_{ir,ij}^{s} \tag{4.12}$$

Therefore, the overall changeover times of the tasks, ranged from *1* to n, on resource i is illustrated as equation (4.13).

$$TT_{ij}^{s} = \left[T_{ij}^{s} \right] = \left[T_{i1}^{s} \quad T_{i2}^{s} \quad \cdots \quad T_{in}^{s} \right] \tag{4.13}$$

(2) Processing time

The overall processing times of task *js*, $j=1,\dots n$, on resource i are demonstrated as equation (4.14).

$$TT_{ij}^{p} = \left[T_{ij}^{p} \right] = \left[T_{i1}^{p} \quad T_{i2}^{p} \quad \cdots \quad T_{in}^{p} \right] \tag{4.14}$$

T_{ij}^{p} represents the processing time of resource i on producing task j. Consequently, the operation time (T_{ij}) should be expressed as (4.15).

$$T_{ij} = T_{ij}^{s} + T_{ij}^{p} \tag{4.15}$$

In order to construct the model schemes for measuring flexibility with attribute consideration at different system levels or with different flexibility types of a manufacturing system, it is necessary to define variables corresponding to the system levels and flexibility types.

4.4.3.3 Dynamic efficiency

Efficiency can be divided into dynamic efficiency and static efficiency. Dynamic efficiency concerns the changing aspect of activities and hence is defined as the effectiveness of changing the system to perform different states. This definition is consistent with Upton's (1995) mobility concept in manufacturing.

Dynamic efficiency could be measured by the ability of a system to change between production tasks. This ability consists of the average changeover time (T_{ij}^{s}) and average changeover cost (C_{ij}^{s}) and has been defined as a changeover funtion (CI_{ij}), meaning the ability of a resource to change itself on producing state *i* to *j*.

(1) Changeover function

Changeover function is defined as the ease, meaning quickness and economy, of changing the system itself for accommodating different circumstances. Equation (4.16) denotes the efforts required to do the changeover of producing task *j* on resource *i*.

$$CI_{ij} = (T_{ij}^{s})^{a}(C_{ij}^{s})^{b} \tag{4.16}$$

a and *b* denote the weights of importance of time and cost for the evaluation of changeover efficiency of resource i, where $a+b=1$, and $a, b > 0$.

The Transition matrixes of time and cost, develop above, are helpful for finding better ways to arrange the schedule for producing different kinds of parts and/or products and for choosing alternative facilities to substitute for failed ones.

4.4.3.4 Static efficiency

Researchers have been more interested in the dynamic concept than the static one, when they have defined manufacturing flexibility. They have defined the dynamic concept as the ability to change in order to neutralize environmental uncertainties. However, the ability to complete tasks should be taken into account as well.

Static efficiency is related to the processing aspect of activities. It concerns the ability to complete an operation function. An operation function could be defined as a processing function and expressed by processing time (T^p) and processing cost (T^c). However, there exists a trade-off between these two elements. A manufacturing system can either invest greater capital in advanced manufacturing technologies to trade operation times off or spend less money to use a lower level machining center to endure longer processing times. The choice managers make depends on the strategies they have adopted.

Processing function

The processing function is defined as the ability to finish a task on a resource. It is depicted as time spent and cost consumed to complete the tasks. Equation (4.17) represents the processing ability of performing task j on resource i.

$$PI_{ij} = (C_{ij}^{p})^{a}(T_{ij}^{p})^{b} \qquad (4.17)$$

where a and b also represent the weighted importance of the cost and time factor respectively, $a+b=1$, and a, $b>0$.

It can be seen that the developed structure of the efficiency framework is so complicated that it would be easier to apply an approach of non-theoretical production function for the efficiency evaluation. The Data Envelopment Analysis (DEA) approach is the most suitable candidate. The variables developed above will be applied in the DEA model, which will be explored in the following section.

4.4.4 Measurement method - DEA approach

The DEA approach is a promising method for measuring the efficiency of a system. The basis for the evaluation is a comparison with peer groups, rather than with theoretical values.

4.4.4.1 The efficiency frontier approach

Farrell (1957) is the pioneer of the efficiency frontier approach. He has demonstrated two forms of productive efficiency which can be measured, namely technical efficiency and allocative efficiency. The efficiency frontier, as the standard, is defined as the minimum unit-output-input requirement. Therefore, productive efficiency is defined, in Farrell's (1957) approach, as the comparison of the performance of actual establishments with the best-practice standard observed or frontier production function in practice, rather than taking the theoretical standard as the point of reference.

To better illustrate the approach, this research takes the example of a deterministic non-parametric frontier model, depicted by Forsund et al. (1980). Consider a firm using two inputs x_1 and x_2 and producing one product y, and assume its production frontier function is $y = f(x_1, x_2)$. Farrell (1957) assumed that the frontier function is characterized by constant return to scale; therefore, the function may be rewritten as $1 = f(x_1 / y, x_2 / y)$, a unit isoquant, represented as frontier technology and denoted UU' in Figure 4.4, whereas PP' represents the ratio of input price.

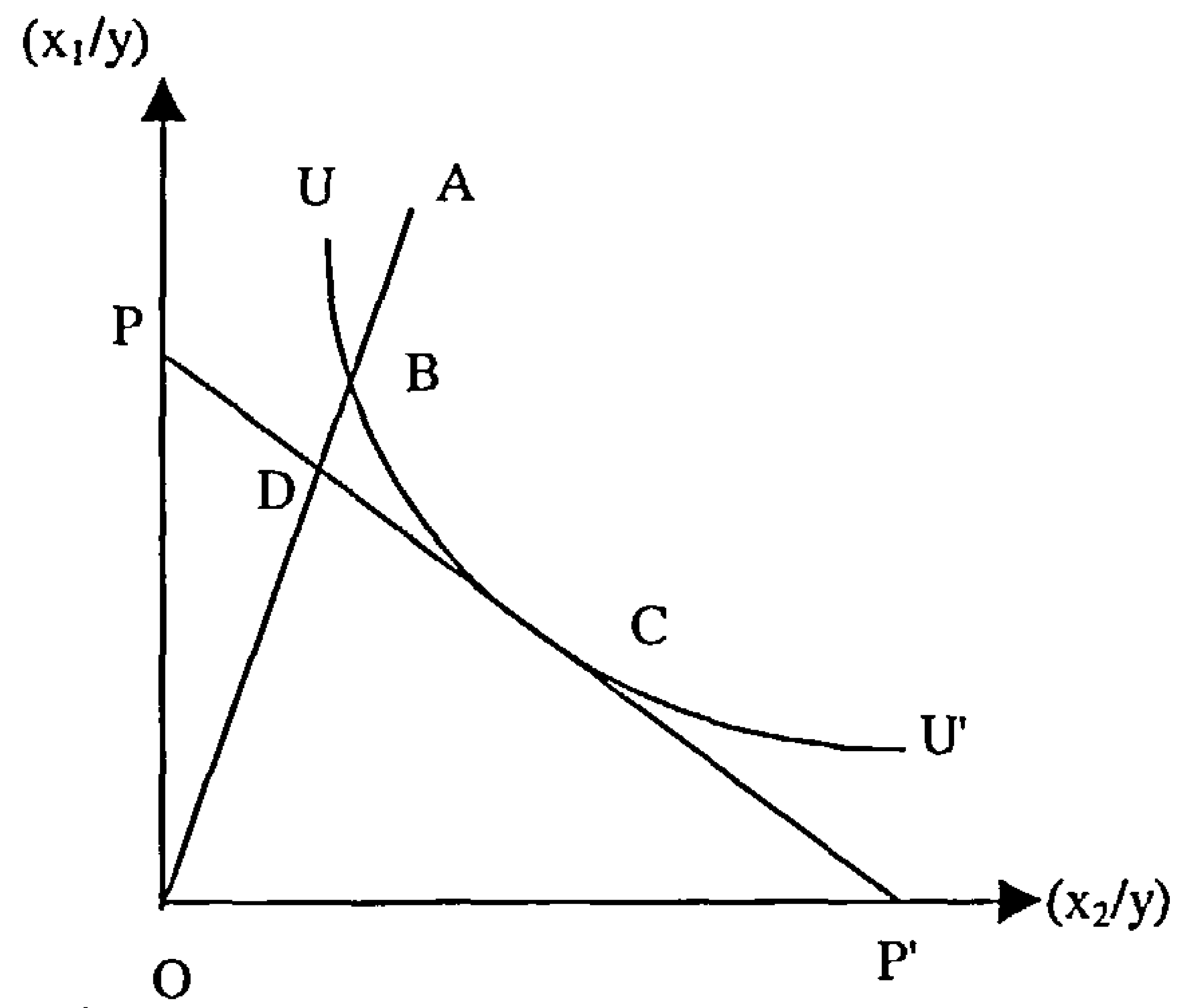


Figure 4.4: Isoquant production frontier function

In Figure 4.4, point A represents firm A using (x_1^0, x_2^0) to produce y^0. Then, the technical inefficiency can be measured by the ratio OB/OA, meaning the ratio of inputs needed to the inputs actual used. And the ratio OD/OB measures allocative inefficiency, since the cost at point D is the same as that of the allocatively efficient point C, but less than that at point B. Thus, points A, B and C in Fig. 6 represent three forms of efficiency combination. Point A indicates that firm A is both technically inefficient and allocatively inefficient, point B indicates that firm B is technically efficient, but allocatively inefficient, and point C represents the only firm that is both technically efficient and allocatively efficient. Finally, OD/OA measures total efficiency.

One of the advantages of Farrell's (1957) approach is that it imposes no functional form on the data, due to the assumption of constant return to scale. By relaxing the assumption, there are a number of works that have been done to allow for a deterministic parameter frontier function estimation (Aigner and Chu, 1968), deterministic statistical frontier estimation (Afriat, 1972; Richmond, 1974; Schmidt, 1976; and Greene, 1980), and stochastic frontier estimation (Aigner et al, 1977; and Meeusen and van den Broeck, 1977).

4.4.4.2 The DEA model

Farrell (1957) specified a locus of minimum unit-output-input as a unit isoquant, defining the production frontier. Following this idea, Charnes et al. (1978) introduced the DEA model. The reason that this research applies the DEA approach as the measurement method is because the DEA approach has the advantage that it is able to consider multiple input and multiple output simultaneously and there is no need to have a theoretical production function before the evaluation. In the DEA model, first, a system is defined as a decision making unit (DMU); second, it must have input and output variables for the DMUs. The ability to put in or take out one of the parameters of the model for different characteristic consideration is another of its flexible advantages. With these, we can measure the efficiency value of a DMU against the best practice in the peer group (Farrell, 1957). In brief, the basic model (CCR) Charnes et al. (1978) is described as follows.

Suppose that there are m systems being evaluated, each system uses r inputs and produces s outputs. Then, the efficiency of system 0 will be:

$$Max \quad e_0 = \frac{\sum_{l=1}^{s} u_l y_{l0}}{\sum_{k=1}^{r} v_k x_{k0}} \tag{4.18}$$

subject to

$$\frac{\sum_{l=1}^{s} u_l y_{lj}}{\sum_{k=1}^{r} v_k x_{kj}} \leq 1, \ j = 1,\dots, m,$$

$$u_l > 0, l = 1,\dots s,$$

$$v_k > 0, k = 1,\dots r.$$

where y_{lj} is the amount of the lth output for the jth system, x_{kj} is the amount of the kth input for the jth system, and u_l, v_k, are variable weights to be determined by the solution to the above maximization equation.

In equation (4.18), there are m systems being evaluated, and the optimization is therefore performed m times resulting in optimal weights u_l^*, v_k^*, and the efficiency value e_0^* for the system being determined as a result. This optimization implies that the system is "technically efficient", if it cannot increase any output or decrease any input without reducing other outputs or increasing other inputs.

Equation (4.18) is a fractional nonconvex programming one. Charnes et al. (1978) show that it can be transformed into a linear programming equation as follows, and can then be solved using commercial linear programming software:

$$Min\ g_0 = \sum_{i=1}^{m} \omega_i x_{io}, \tag{4.19}$$

subject to

$$-\sum_{l=1}^{s} u_l y_{lj} + \sum_{k=1}^{r} \omega_k x_{kj} \geq 0,\ j = 1,\ldots m,$$

$$\sum_{l=1}^{s} u_l y_{lo} = 1,$$

$$u_l > 0, l = 1,\ldots, s,$$

$$\omega_k > 0, k = 1,\ldots, r.$$

Charnes et al. (1978) show that:

$$e_o^* = 1 / g_o^* \tag{4.20}$$

$$\omega_k = t\, v_k,\ k = 1,\ldots, r, \tag{4.21}$$

and

$$\mu_l = t\, u_l,\ l = 1,\ldots,s, \tag{4.22}$$

where:

$$t^{-1} = \sum_r u_r y_{ro}. \tag{4.23}$$

4.4.4.3 The application of DEA in rating manufacturing system efficiency

This thesis considers that the measurement of efficiency should include time and cost simultaneously, because time and cost are inversely related, which was suggested by Gupta and Goyal (1989).

(1) Graphical illustration

Following the viewpoint of Farrell (1957), we define a production function as $Q=f(t, c)$, where t and c represent time and cost respectively, when the system produces the output of Q. The function can be written as $1=f(t/Q, c/Q)$. We can therefore generate a piecewise production frontier function, an isoquant production line, UU', as shown in Figure 4.5. The technical efficiency ratio of a DMU is measured by OB/OA, the minimum usage of inputs (time and cost per unit production) of the frontier, which comes from the piecewise production function of the peer group, divided by the actual usage. By comparing OD/OA, the total system efficiency can be evaluated, where P_tP_c represents the price curve.

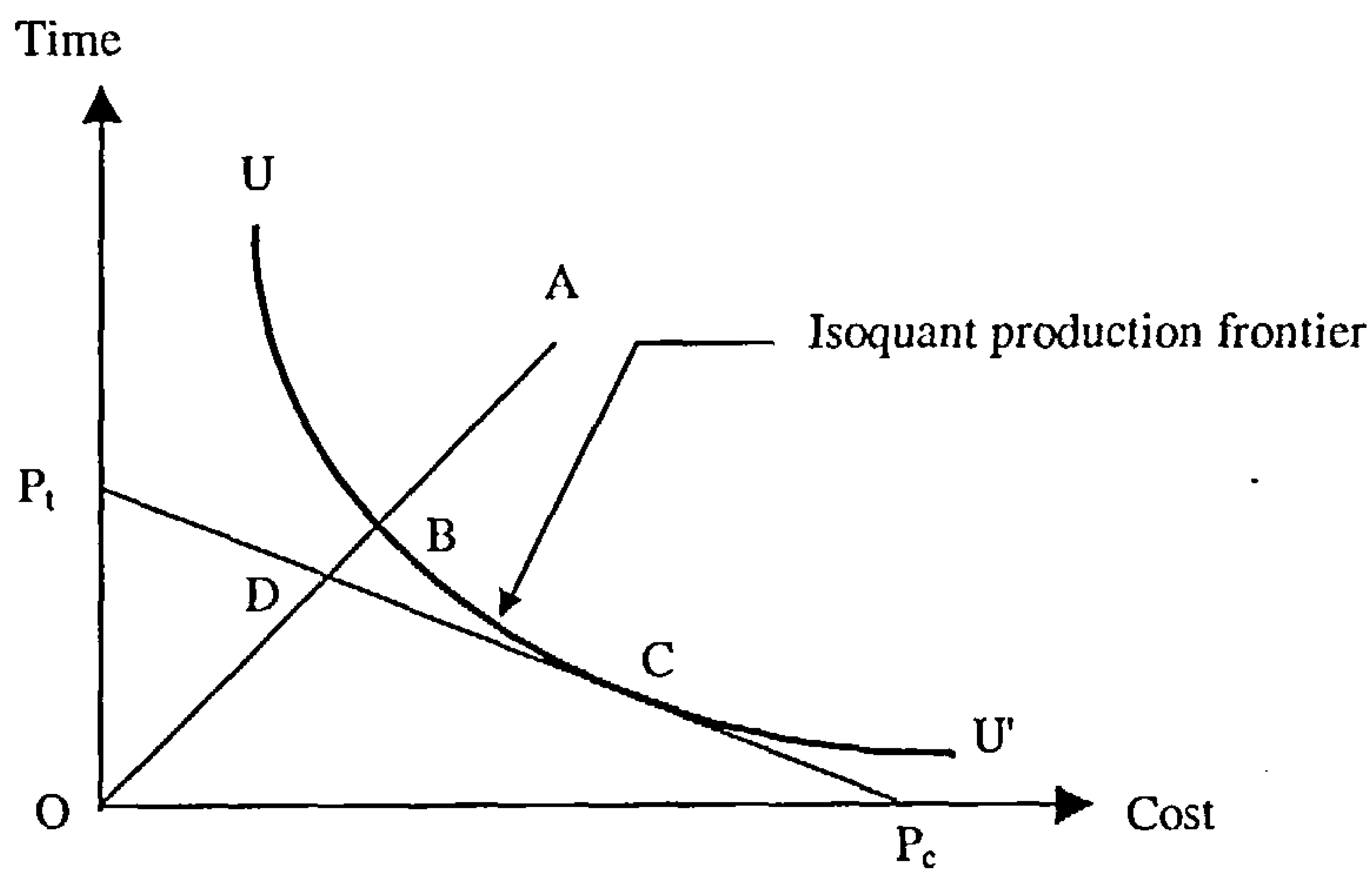


Figure 4.5: Isoquant production frontier with time and cost

Figure 4.5 depicts a one-kind per unit production. The model can be expanded to explain the proliferation of the system. When other kinds of product are added to the system, its unit production could be increased, due to the increase of changeover time and cost. A proliferation curve of the system therefore can be obtained as in Figure 4.6. The $U_1U_1^{'}$, $U_2U_2^{'}$, $U_3U_3^{'}$, and $U_4U_4^{'}$ represent one-kind, two-kind, three-kind and four-kind unit production curves respectively.

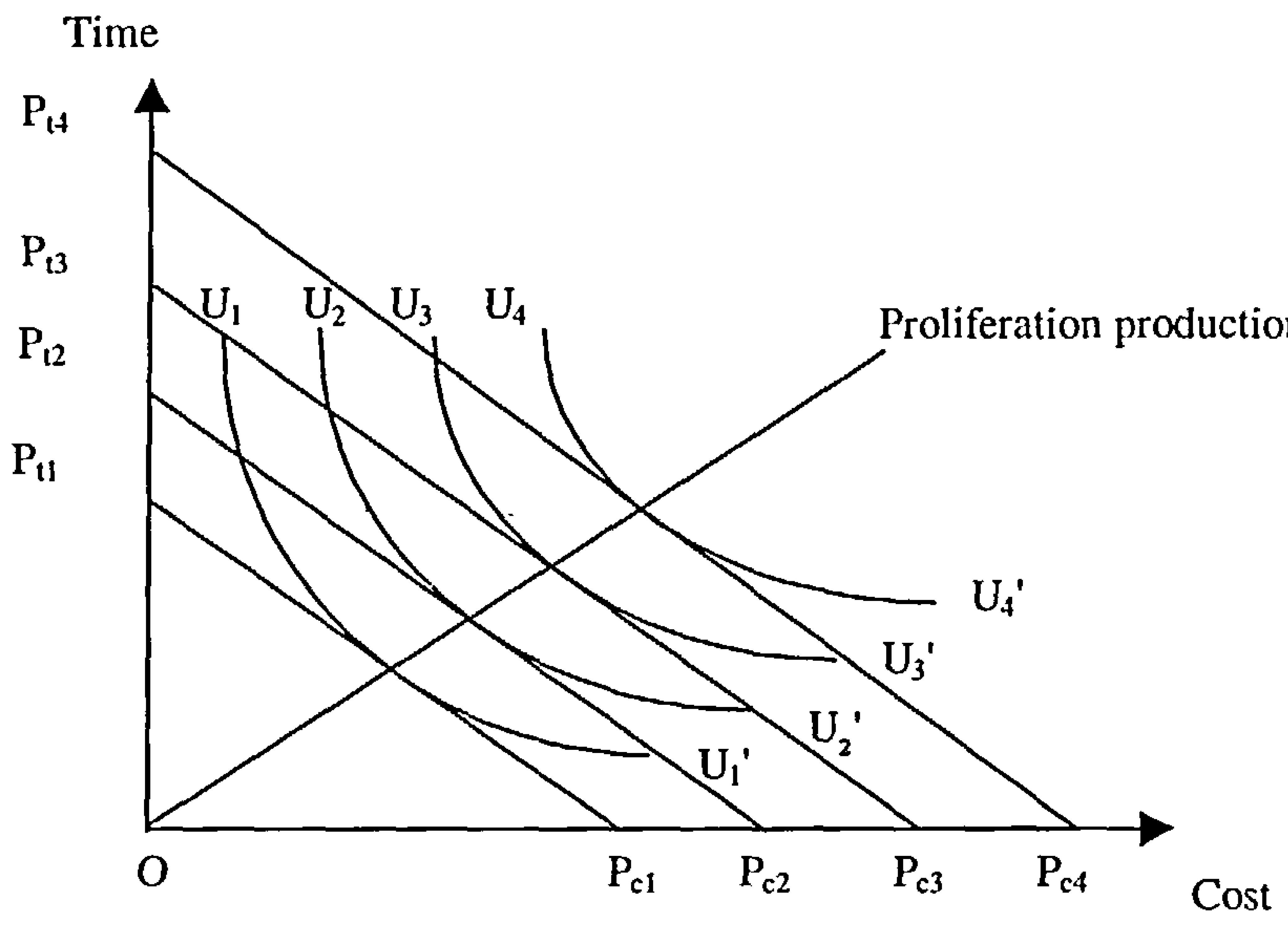


Figure 4.6: Proliferation production curve

4.4.4.4 The application of DEA to system efficiency

In general, the DEA model is for the evaluation of the efficiency of a system, a decision making unit (DMU). In this research, however, one *state* is regarded as a DMU when the system is performing its correspondent *task*, for example, producing products, introducing new products, changing the production volumes, etc., whenever the specific flexibility is measured. A *task* performed by the system consists of a *range* of *states*, i.e., a *range* of DMUs. When a system is producing one *state*, it will necessarily consume *cost* and *time* to produce a certain amount of output.

Theoretically, a system is designed to produce specific types of output. The system can therefore perform those specific types of output with the most efficiency. Nevertheless, when the system produces other types of *state*, or expands the *range* of *states*, the efficiency will be reduced, namely, increasing *cost* and *time* to produce an equal amount of the *state* output, or decreasing the amount of output with the same amount of *cost* and *time*. Therefore, the changeover during the *states* theoretically decreases efficiency.

In practice, if a system can reduce the increasing cost and time of the changeover as much as possible, the system will be able to maintain its original high efficiency. Therefore, if the *range* of states can be expanded by a system by reducing the deficiency when switching on performing the *states,* the system increases its flexibility.

An efficiency measurement framework is depicted in Figure 4.7. Figure 4.7 illustrates the requirement of input and output variables for the measurement model which will rate the efficiency of a system i when performing the state j, denoted as T_{ij}.

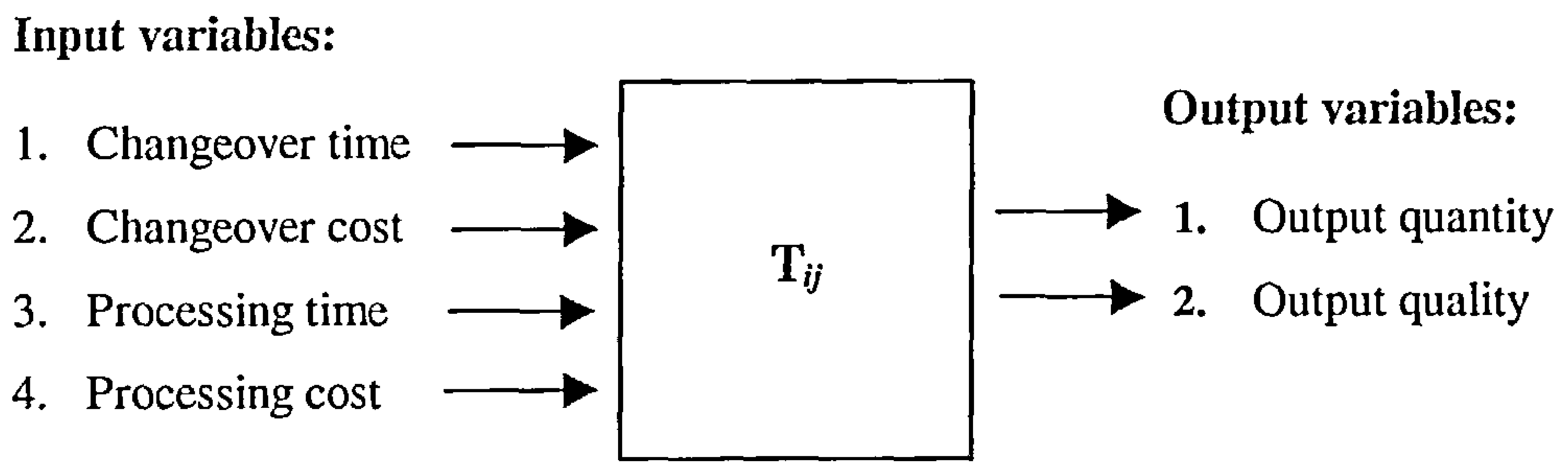


Figure 4.7: A description of the variables of the DEA model

4.4.5 System efficiency model

The DEA model is for rating the efficiency value of a system on performing a particular state or, more generally, a task. As long as all efficiency values have been computed by the DEA model, an efficiency table can be obtained, as in Figure 4.8.

		Outputs			
		S_1	S_2	⋯	S_n
Inputs	R_1	e_{11}	e_{12}	⋯	e_{1n}
	R_2	e_{21}	e_{22}	⋯	e_{2n}
	⋮	⋮	⋮	e_{ij}	⋮
	R_m	e_{m1}	e_{m2}	⋯	e_{mn}

Figure 4.8: An efficiency table of a manufacturing system

The efficiency of a manufacturing system is thus able to take the mean value of the efficiency table.

$$E = \frac{1}{n \times m} \sum_{i=1}^{n} \sum_{j=1}^{m} e_{ij} \tag{4.24}$$

With respect to manufacturing systems, efficiency follows the focussing of the system on the tasks that the systems are really good at. The idea is consistent with the focused factory, proposed by Skinner (1974). It would not be possible to do everything well when resources are limited. It would make the systems confused and separate their efforts into different areas (Skinner, 1974). Efficiency is the main factor a system should pursue to achieve the so called "*Economies of Scale*", which is based on a cost orientation to achieve effective competition. Figure 4.9 depicts an efficient system.

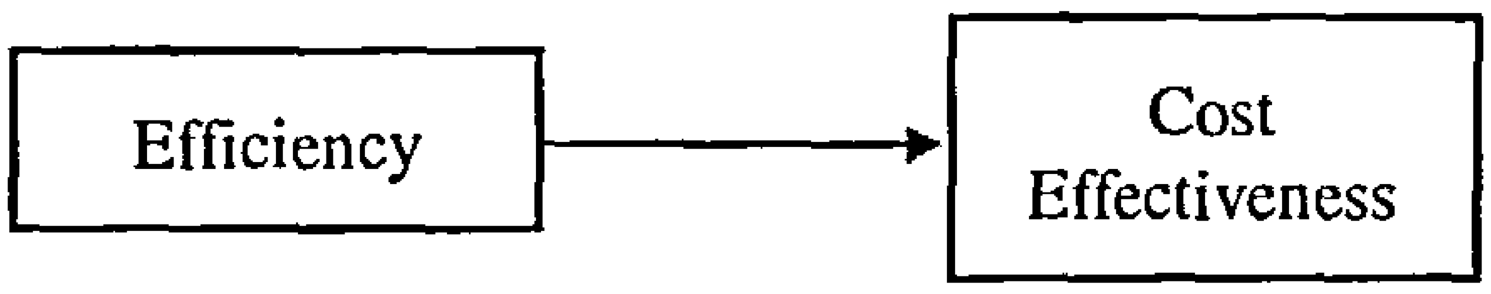


Figure 4.9: An efficient manufacturing system

However, for a flexible system, it should be efficient at doing versatile things. Otherwise, if the system is efficient on performing a narrower range of tasks, it can only be viewed as a focused system, whereas a versatile system, rather than a flexible one, is able to produce a wide range of tasks, but not all at a high efficiency (Tincknell and Radcliffe, 1996).

4.5 The development of versatility measurement

4.5.1. Concept

When the market is entering a more dynamic situation, i.e., there is increasing diversified demand, shorter product life cycle, greater segmented markets, the systems have to cope with these changed circumstances by producing many different types of products for their customers.

A versatile system is a system which is able to produce a wide range of different kinds of outputs. More generally, the outputs are defined as a set of tasks. The meaning of the tasks is different at different system levels, and should be defined when doing the measurement of a systems' flexibility. This is because systems at different levels produce different kind of outputs, e.g., a machine produces operations, a manufacturing cell produces parts or parts families, and a plant produces products, etc.

The set of output tasks produced by a system can be expressed as a vector of $\Gamma(S_i)$, and

$$\Gamma(S) = \Gamma(O_{i1}, O_{i2}, \ldots, O_{in}) \tag{4.25}$$

$\Gamma(S_i)$ should have the property that the wider the range of the tasks in the output set is, the more versatile the system. This means that the system is able to provide more types of tasks for its customers. If a system can perform a wider range of contained tasks at each level, in terms of the variety of products, manufacturing in different volume, or a number of alternative routes, it exhibits more flexibility than those which perform a narrower range. In short, the wider the range of tasks a system achieves, the more flexibly it has.

4.5.2 Method

The entropy approach, defined by Shannon (1948) in information theory, is a proper method to evaluate versatility. It has been successfully applied to measuring the diversification of a firm in the marketplace (Rumelt, 1974; Jacquemin and Berry, 1979; Rumelt, 1982; and Palepu, 1985) and the approach has been clearly described in economics (Theil, 1967).

The entropy approach has also been used to describe the decision making options for measuring the specific types of flexibility in manufacturing systems, namely routing flexibility, loading flexibility and operation flexibility, by Kumar (1986, 1987), and Yao

(1985). In addition, the applications of part flexibility, processor flexibility, mix flexibility, volume flexibility and expansion flexibility were conducted by Benjaafar and Talavage (1992a, 1992b).

The entropy function of a system can be described as:

$$S(P_1, P_2, ..., P_n) = -\sum_{i=1}^{n} P_i \log P_i \tag{4.26}$$

S is a finite discrete probability distribution and P_i represents selecting the various options, reflecting the freedom of the population. P_1, P_2,..., P_n represent the freedom of choosing the options. All these Pi's are fractions or shares, are positive, $0 \leq P_i \leq 1$, and can be normalized such that they add up to unity, $\sum_{i=1}^{n} P_i = 1$, $i=1,...,n$, and could be considered as probabilities. In general, the larger the number of available options, the greater should be the flexibility.

The reason why Shannon's (1948) entropy approach is suitable for the measuring of versatility is that it contains the following properties (Kumar, 1986):

(1) P_is, $i=1,...n$, denote a continuous probability function.

(2) The function will be at its maximum, when $P_1=P_2=...=P_n=1/n$.

$$S(p_1, p_2, ..., p_n) = \log n \tag{4.27}$$

(3) The maximum value of this function should increase as n increases.

(4) The function should be at its minimum when one of the possibilities is unity and all other probabilities are zero and this minimum value of the function should be zero.

(5) The function should not change when an additional option with zero probability is allowed.

In Kumar's (1986, 1987) entropy method, he demonstrated that the more the alternative decision options, the greater the value of entropy, i.e., the greater the flexibility. Such a consideration is the same as the range of the tasks; however, the method did not take into account the efficiency dimensions.

4.5.3 Measurement model

In order to formulate a versatility measurement model, the efficiency value (e_{ij}) has been applied to the model instead of the set of output performance factors, as shown in Figure 4.1. The versatility of a manufacturing system $V(S_i)$ is therefore formulated as (4.28):

$$V(S_i) = -\sum_{j=1}^{m} \alpha_{ij} \log \alpha_{ij} \tag{4.28}$$

where

$$\alpha_{ij} = e_{ij} \Big/ \sum_{j=1}^{m} e_{ij} \tag{4.29}$$

When the system competes in a turbulent environment it needs both efficiency and versatility meaning "*Economies of Scope*". In order to achieve effective competition, the system should be efficient and versatile. Figure 4.10 depicts such a circumstance. Therefore, both efficiency and versatility are two basic factors depicted in a flexible system.

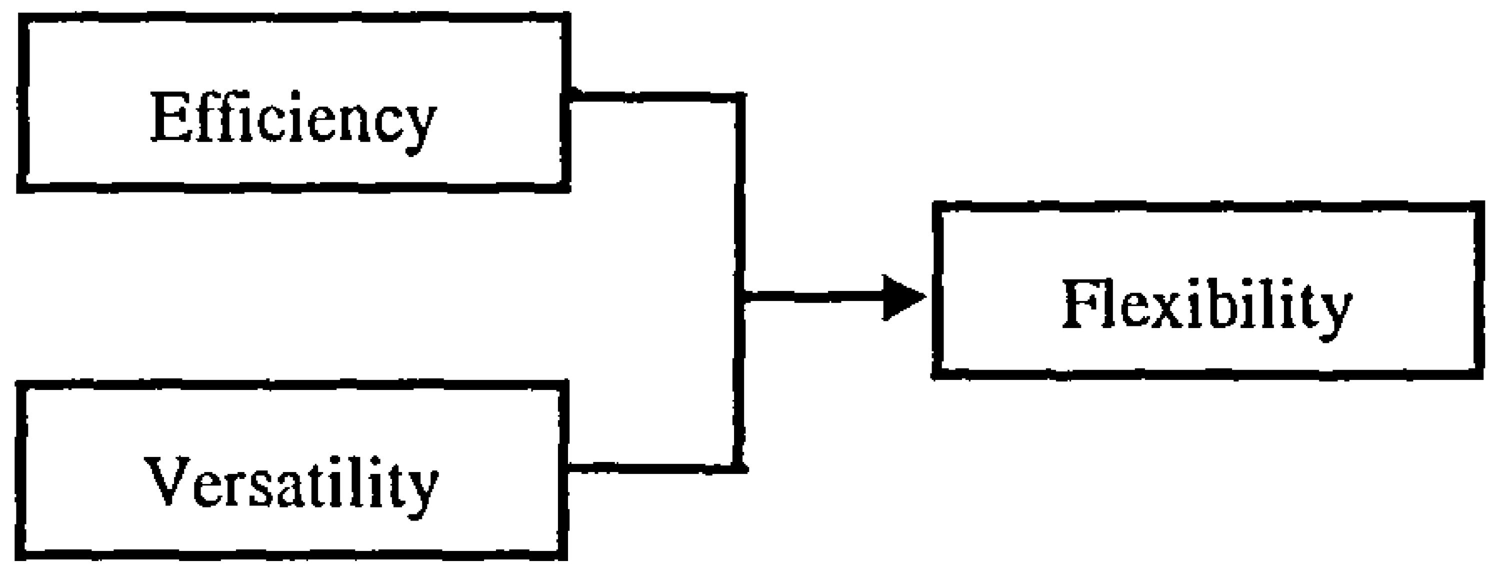


Figure 4.10: A basic flexible manufacturing system

4.6 The development of redundancy measurement

4.6.1 Concept

One of the virtues of a flexible system is that it is able to neutralize the unpredictable circumstances caused by environmental uncertainties. A system which is involved in such circumstances, is not able to tell what will occur next in terms of product changes or order quantity difference, or even equipment failures or labor absenteeism, etc. One of the abilities of a flexible system comes from its redundancy.

If the only certain thing is that all the resources in the system are 100 percent reliable, a system may not require redundancy. Otherwise, even if the resources in the system are versatile and efficient, it will call for redundant resources in the forms of capacity, capability or utilization (Slack, 1989). A system with capacity is a system which has the ability to adjust its production speed; capability is the ability to adjust itself to produce different types of product; while utility takes the form of a mix of unused capacity and capability.

A typical form of capacity is the ability to change the production throughput rate. An increase of the throughput rate relies mainly on adding resources in terms of manpower and/or equipment to the system, and *vice versa*.

4.6.2 Method

Redundancy has been defined as the presence in the system of many resources which all have the common capability to produce the same tasks. The system depicted in Figure 4.1 is a system which embodies redundant resources. The resources of S_is, $i=1,...n$, are all capable of producing all T_js, $j=1,...m$. The vector T_j, equation (4.30), illustrates the whole resources in a system which is capable of producing the output tasks with different efficiency values.

$$T_j = \begin{bmatrix} e_{1j} \\ e_{2j} \\ \vdots \\ e_{nj} \end{bmatrix} \tag{4.30}$$

The requirement for the measurement model should have the property of increased flexibility when increasing the redundant resources in the system. The entropy approach, explored above, is also suitable for the measurement of redundancy.

4.6.3 Model

$$R(T_j) = -\sum_{i=1}^{n} \beta_{ij} \log \beta_{ij} \tag{4.31}$$

where

$$\beta_{ij} = e_{ij} \Big/ \sum_{i=1}^{n} e_{ij} \tag{4.32}$$

When the system has been combined with some identical resource, this ensures that the system is able to run in a smooth condition. Unless the system elements are all fully reliable, it is necessary to have redundant resources. Therefore, redundancy guarantees that the system will keep running at a high efficiency all the time, even though the resource elements are not of high reliability. Figure 4.11 shows the relationships.

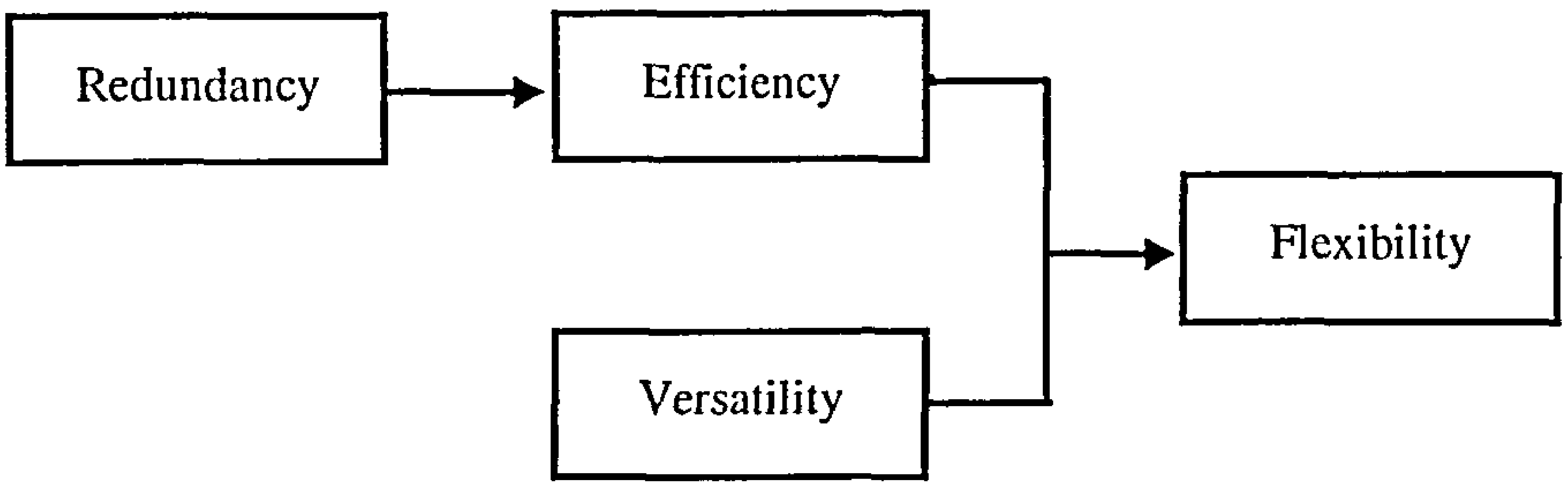


Figure 4.11: A flexible manufacturing system with redundancy

4.7 The development of variety measurement

4.7.1 Concept

Variety measurement captures the differences between output tasks. In the opposite way, it is the measurement of commonality between output tasks. The development of such a measurement will deviate with different levels of the manufacturing system. For example, at the machine group level, the output tasks are a set of operations, at the process level, they relate to a set of parts and at the plant level, they are associated with a set of products.

4.7.2 Method

The method of measuring the differences between products proposed by Das (1996) should be a function of (1) the product handling procedure, (2) the operations, (3) the processing times, (4) the processing skills, and (5) the physical nature of products. These lead the idea of this research to construct the differences when measuring the flexibility at different system levels, because "product" is the highest level of the production structure.

However, it could be difficult, if the factors mentioned above have all been applied to the measurement of the difference between two products, especially when the compared products are complicated, such as vehicles. This thesis is not intended to apply those five criteria into the measurement models. Rather, this research will consider Gupta's (1993) suggestion that the number of products in the product set produced by the system, the degree of component commonality and the degree of processing commonality act as the functions for the measurement of the difference. Since the first factor stated by Gupta (1993) and the processing times have been included in the versatility and efficiency measurements respectively in the present research, this research therefore considers that **the variety measurement is the inverse of commonality with respect to the operations among the output task set.**

4.7.3 Model

Generally, variety measures the difference of the output tasks. When the differences of the components contained in the compared tasks can be defined, the value of variety can be identified. Equation (4.33) demonstrates the general model for the measurement of the difference between two compared output tasks. It is represented by the ratio of common components to the given component of the pair of tasks.

$$d_{ij} = 1 - \frac{S_i \cap S_j}{S_i} \tag{4.33}$$

where d_{ij} represents the difference between the output tasks i and j. Moreover, S_i and S_j denote the set of compared features that belong to tasks i and j respectively. The numerator is represented as the intersection of S_i and S_j, while the denominator is the evaluation task i.

Consequently, a difference matrix could be obtained and provide a clearer understanding of the concept.

$$[D]=\begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & d_{ij} & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \tag{4.34}$$

The measurement of a particular task i in the task set produced by the system is therefore measured as (4.35).

$$d_i = \frac{1}{n-1}\sum_{j=1}^{n} d_{ij} \tag{4.35}$$

The method of measuring the difference among the output tasks of a manufacturing system is calculated as the mean value of the total differences in the difference matrix. As the d_{ij} could not be the same as d_{ji}, the average among the differences should be:

$$D = \frac{1}{n(n-1)}\sum_{j=1}^{n}\sum_{i\neq j}^{n} d_{ij} \tag{4.36}$$

However, the difference will deviate at different system levels, as they have some other specific considerations. By following the structure of a production system, it is possible to generate the difference structures at different system levels and different flexibility types. Briefly, a product consists of several parts and a part consists of several operations. A process consists of several machines and operators and a flexible machine or operator is able to perform several different operations to produce different kinds of products. Hence, different processes may produce an identical part/product. Moreover, a production route also comprises a set of operations, meaning a set of machines to visit.

A part can be expressed as a set of operations and hence can be expressed as a set of capable routes to produce the part. Therefore, when the differences between two products can be identified, it is possible to develop the differences between the output states at the lower levels, and vice versa.

If a further investigation has been taken to look at the relationship between versatility and variety, versatility should be ensured by the differentiation of its outputs. That is the need of variety. Variety is a way of underpinning the system's versatility. If it has been counted that system A produces more types of product than system B, system A could be thought more flexible than system B by only counting the number of outputs from the systems. However, this would be wrong if system A produces almost the same products in features. Therefore, variety enforces the versatility of the system as depicted in Figure 4.12.

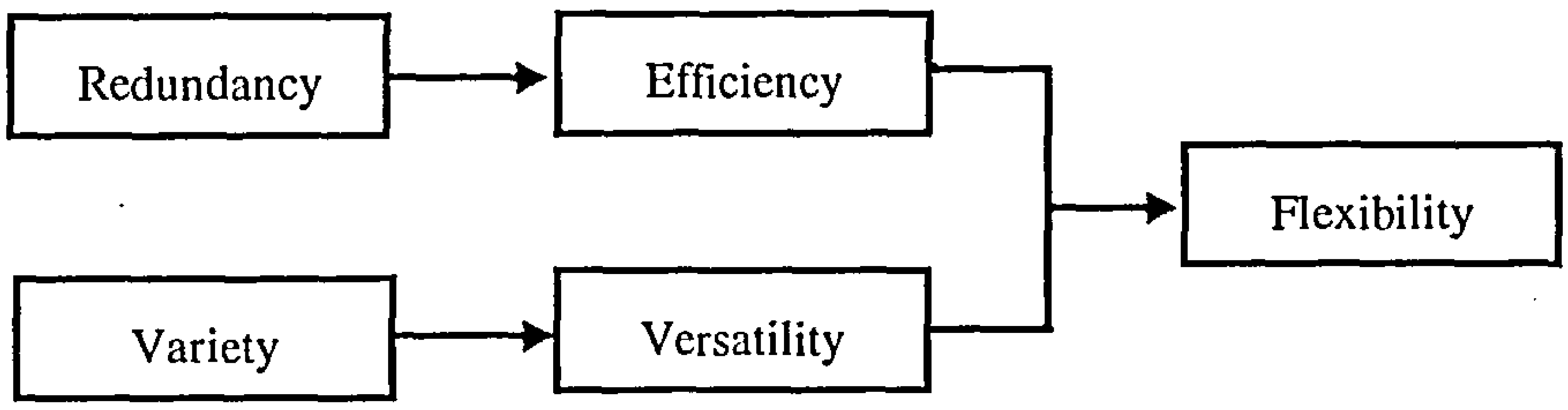


Figure 4.12: A flexible manufacturing system with redundancy

4.8 The development of mobility measurement

4.8.1 Concept

Mobility has been defined as the ability to move of a set of resources when they are needed. The requirement arises when machine failure occurs or another layout is necessary for changing the production tasks to accommodate a different product mix or the introduction of a new product.

Upton (1994) used the term mobility to formulate the model of a system's ability to change. The model of mobility proposed by Upton (1994) is focused on setup time and the objective has been applied at the machine level. This is rather a narrow concept as the focus is on the setup for the next operation of a machine. Such a concept could be expanded to higher levels.

The mobility concept with respect to this research concerns three aspects, namely moving the facilities, re-setting up the processes and re-arranging the production layout.

4.8.2 Method

A method to recognize such an ability is to list a matrix, which is depicted by two factors, namely the places that a set of resources is available to move to, and the ease of moving. The former is restricted by its own operation function and the sequence of the operations, while the latter is characterized as the ability to move and setup, including transportation time and setup time. The matrix is illustrated as follows.

$$M^r = \left[m_{ij}^r\right] = \begin{bmatrix} m_{11}^r & m_{12}^r & \cdots & m_{1n}^r \\ m_{21}^r & m_{22}^r & \cdots & m_{2n}^r \\ \vdots & \vdots & \cdots & \vdots \\ m_{n1}^r & m_{n2}^r & \cdots & m_{nn}^r \end{bmatrix} \tag{4.37}$$

where m_{ij}^r represents the time spent for resource r to move from location i to j.

Therefore, the mobility of a resource can be measured by the area it can reach and the speed of switching between the locations.

4.8.3 Model

There are two factors for the measurement model, namely the number of candidate places for the movements of a set of resources and the ease of the movements, to keep the production efficient. Mobility is therefore measured by the factors of coverage and speed.

4.8.3.1 Coverage measurement

Coverage is measured by the percentage of the area that the resource is able to reach within a production site or a production network. Alternatively, it could also be measured by the ratio of the number of places (N_p) where the resource can be, to the total number of places in the system (T_p).

$$MC^r = \frac{N_p^r}{T_p^r} \qquad (4.38)$$

4.8.3.2 Relocation measurement

Moving a resource consumes both time and cost. However, time seems significantly more important than cost in explaining the concept of mobility. Mobility is defined in this research in terms of quickness. Relocation is the measurement of time required for changing the place. The movement time (MT) measured includes transportation time and setup time for the readiness of the required operations. MT is formulated as the average switch time from one place to any other places.

$$MT_i^r = \frac{1}{p}\sum_{j=1}^{p} m_{ij}^r \tag{4.39}$$

where p represents the number of places where resource r is able to replace the other resources.

Therefore the mobility of a resource r is measured by the following equation (4.40).

$$M^r = \lambda_1 MC^r + \lambda_2 MT^r \tag{4.40}$$

where $\lambda_1, \lambda_2 \geq 0$ and $\lambda_1 + \lambda_2 = 1$. λ_1 and λ_2 denote the weighted importance of the coverage and relocation factors of the mobility attribute.

In order to underpin the efficiency of the system, other than having the redundancy attribute, it is necessary to have the ability to move the resources when breakdowns of the arranged facilities occur. Figure 4.13 shows the further relationships of the proposed attributes so far.

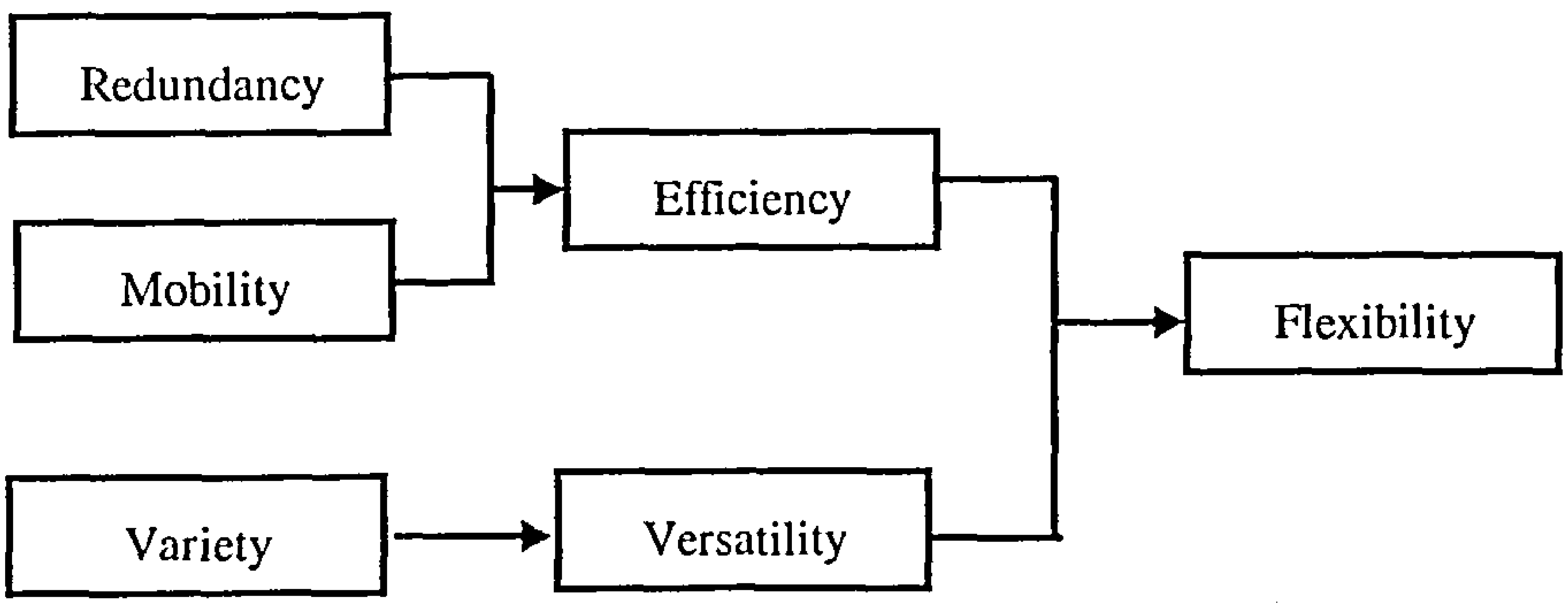


Figure 4.13: A flexible manufacturing system with redundancy

4.9 The development of autonomy measurement

4.9.1. Concept

Any product can theoretically be produced in a manufacturing system, even a huge or complicated one. However, it does not seem to be a good choice in practice, because the factory might be so huge that it would not be simple to manage, and costs would increase tremendously. Empirically, an end product producer, say a vehicle manufacturer, is unlikely to produce all the components required for the assembly of a vehicle. Normally, most of them will be bought from its suppliers. Consequently, managers have to make the decision of "make or buy".

There is a production process span, which includes all the necessary operations from ordering the materials to the end product. The autonomy depicted here explains what span the production system is able to cover within the whole theoretical process.

4.9.2 Model

Autonomy can be measured as the percentage of the operations performed by the system to the total operations of the product. If the system can completely perform the operations, it exhibits full autonomy, and its value will be represented as 1.

$$A_i = \frac{\bigcup_{r \in \eta_i} O_{ir}}{\bigcup_{r \in \eta} O_{ir}} \tag{4.41}$$

where η represents the whole set of operations for producing product *i*, while η_i the set of operations performed by the evaluated system. In equation (4.41), the numerator denotes the union of components set of product *i* produced by the system, while the denominator denotes the total components set of product *i*.

However, in some industries, e.g., the vehicle industry, the ratio of A_i could be quite small, as they buy the great majority of their components and assemble them into a product. It would be more reasonable for the system to be evaluated in comparison with the peer group in the industry.

$$A_i' = \frac{\bigcup_{r\in\eta_i} O_{ir}}{\bigcup_{r\in\eta_j} O_{ir}} \tag{4.42}$$

where η_j represents the set of operations performed by the highest value of A_i for producing product *i* in the industry.

If the computation is too complicated for the evaluation, it would be easier to count the number of parts instead for the comparison at plant level, for instance. The ratio could be the percentage of parts produced by the system to the total parts required for producing the product, and then comparing this with the highest value in the industry.

It should be noted that the highest value of autonomy does not represent the most efficient way of production. If the supply chain system is robust and more efficient than that of the product producer itself, it would be better to buy the components and do the assembly work only.

Figure 4.14 represents a basically general flexible manufacturing system from the output of view of physical characteristics.

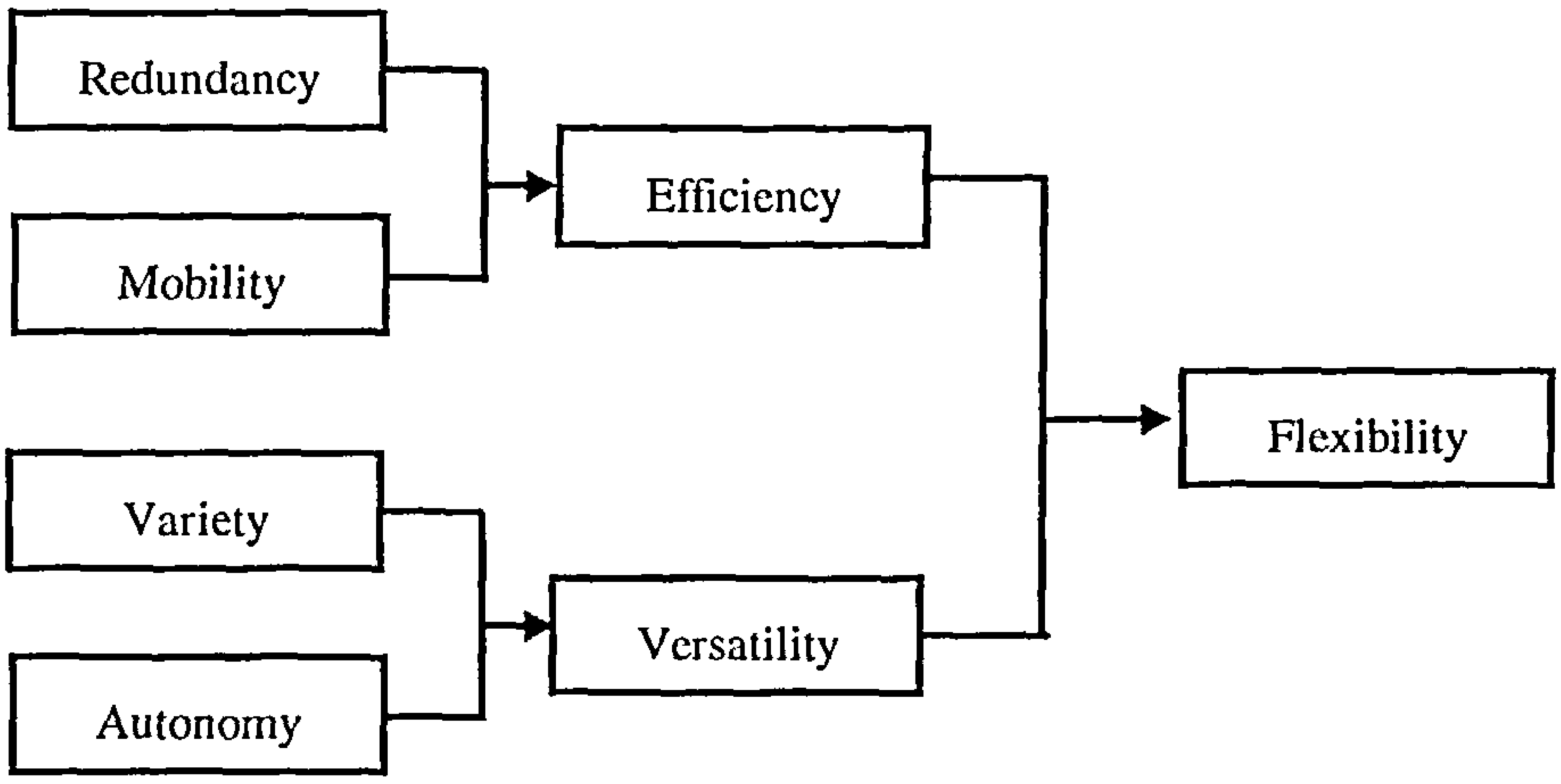


Figure 4.14: A flexible manufacturing system with redundancy

4.10 Probability of occurrence of the tasks

4.10.1 Concept

Probabilities assigned to the tasks set are related to the likelihood of occurrence of the tasks, due to changes in the dynamic environment. The vector of probability should be assigned by managers who need to predict the future demands in the marketplaces, and hence exhibited the effectiveness of the system when coping with dynamic environment. One task could be more likely to emerge in a certain period of time and/or at a certain place, but unlikely to occur in others. When one task is of high occurrence and the system is able to perform it with high efficiency, the system indicates high effectiveness in coping with the forthcoming circumstances.

4.10.2 Method

The assessment of the probability distribution of the occurrence of the tasks in the future markets comes from a recognition of the trend by the managers. One of the tasks of managers is to scan the changes in the environment and decide the course that they want to pursue. The steps in assessing the occurrence of the tasks includes, firstly, a listing of those tasks that are likely to occur in the future, and secondly, a probability distribution of the tasks.

4.10.3 Model

If the set of the tasks of the system has been defined as in (4.43), it is necessary for managers to predict what will be the next tasks mix in the future.

$$T = \begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_n \end{bmatrix} \tag{4.43}$$

As long as the likelihood of the occurrences has been estimated, the probability distribution can therefore be determined as (4.44).

$$P = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} \tag{4.44}$$

where $0 \le P_j \le 1$, and $\sum_{j=1}^{n} P_j = 1$.

Figure 4.15 illustrates a general flexible system which takes into consideration predictions from market information. The occurrence of a product at a plant level, for example, has its probability feature. Therefore for the overall tasks in the system, there is a probability distribution of the occurrences. If flexibility measurement has been considered such a factor for checking the effectiveness of coping with the forthcoming turbulent circumstances, it will be necessary to add this attribute into the measurement model.

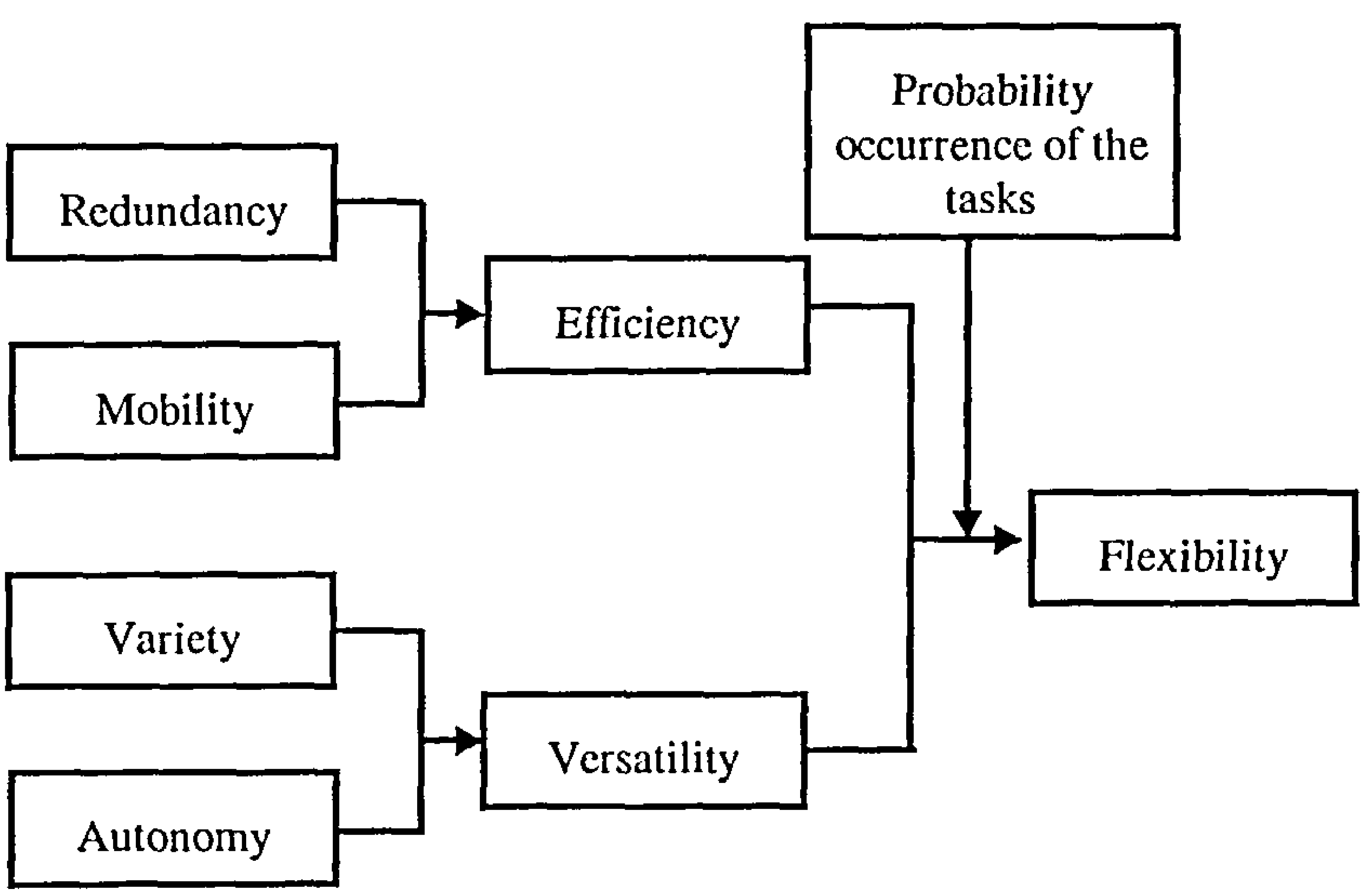


Figure 4.15: A probabilistic general flexible system

4.11 Weighted importance of the tasks set

4.11.1 Concept

Since customers' preferences are changing and difficult to predict, they produce a dynamic environment for a company. In order to cope with these changes effectively, it is necessary for the system to adjust itself to the changing circumstances. For the consideration of competition, a system needs to concentrate its efforts on a certain area and setup the focus on its competitive edge, rather than pursuing tasks everywhere or at any place. A product may have a different importance at different times. For instance, in one period, customers might be interested in product A; however, they turn to product B in the next. This requires a company to check which products are increasingly important or fading out, as it will affect the production system. As long as managers have recognized the changes, the production system can be adjusted to focus on the more important activities in terms of operations, components, process, facilities, etc. consequently.

In another way, senior managers might set up the competitive priorities for their companies. Then, they will distinguish which products are more important than others. Consequently, they assign different importance weights when evaluating the total effectiveness of running the business.

4.11.2 Method

Weights should be set up from the top level of competitiveness. At the top of the levels is the product. In consequence in order to produce the products, production processes, routings, facilities, operations, operation skills and so forth, it is necessary to determine their weights of importance as well. **These weights should be assigned by the operation managers.**

It does not seem sensible to sum up the weights of the tasks to unity, as Mandelbaum and Brill (1989) did. It is the same as taking the average of the tasks weights, if the special case of unifying the weights has been chosen. The reason is that it is unlikely to guarantee flexibility increase by increasing the tasks produced by the system, which does not seem consistent with the properties of measuring flexibility in Brill and Mandelbaum (1990). The method of relaxing the constraints, appeared in Mandelbaum and Brill (1989) and by combining importance weights with the flexibility measurement model is to let $0 \leq W_j \leq 1, j=1, 2, \ldots, n$, where W_j denotes the weight of importance of task j.

4.11.3 Model

Once the output tasks set of the system has been identified as in (4.43), operation managers are able to characterize the importance weights of the tasks for the system. The weights of importance of the task set could be defined as a **vector** W.

$$W = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} \tag{4.45}$$

The weights of the tasks are decided by the managers, taking into account their firms' objectives in terms of profits, market share, growth rate, etc. Figure 4.16 shows the consideration of weights as the importance of the tasks to the company.

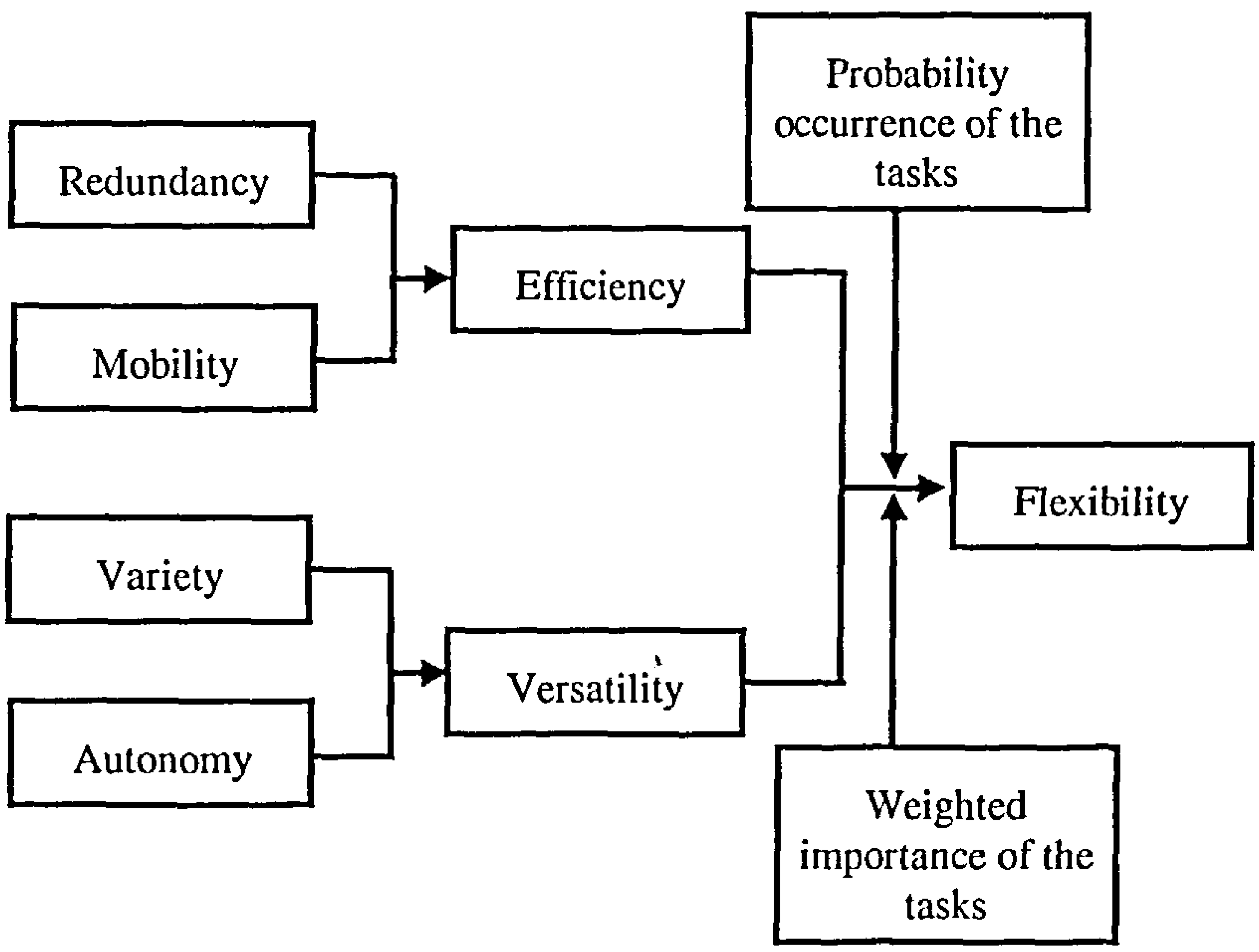


Figure 4.16: A weighted probabilistic general flexible system

4.12 Concluding Remarks

It has been argued by this research that the concept of manufacturing flexibility actually embodies multi attributes, which have been clearly depicted in the last chapter. There are at least ten types of flexibility attributes, namely efficiency, versatility, redundancy, variety, mobility, autonomy, probability assignment and weights of importance, and these have been identified and examined. In this chapter, their measurement models have been demonstrated respectively. It would therefore not be sensible to measure the flexibility of a manufacturing system simply with partial attributes, e.g., efficiency or versatility only, as they capture limited features of the flexibility.

In all, the basic requirement for a flexible system in manufacturing should be to execute a number of versatile tasks at high efficiency. Task variance and self-completion of the tasks are two attributes to consider to enforce versatility. In order to maintain such high efficiency it seems necessary to have alternative and movable resources for the production of the tasks. The **probability of the occurrence** of tasks in the future as estimated by the managers, and the **weights of importance** of the tasks are two more attributes for management consideration. The relationships among these attributes have all been demonstrated step by step. This provides a better understanding of the attributes encompassed in manufacturing systems.

The attributes proposed in the present research could lead to a different way of thinking in this field. It seems to make the flexibility concept in manufacturing systems clearer and the measurement more sensible.

4.13. References

Afriat, S. N. (1972), "Efficiency Estimation of Production Functions", *International Economic Review*, Vol. 13, no. 3, Oct., pp.568-598.

Aigner, D. J. and Chu, S. F. (1968), "On Estimating the Industry Function", *American Economic Review*, Vol. 58, no. 4, Sept., pp.826-839.

Aigner , D. J.; Lovell, C. A. K. and Schmidt, P. J. (1977), "Formulation and Estimation of Stochastic Frontier Production Function Models", *Journal of Econometrics*, Vol. 6, no. 1, July, pp.21-37.

Atkinson, J. (1985), "Flexibility Planning for an Uncertain Future", *Manpower Policy and Practice*, Vol. 1, Summer.

Barad, M. and Sipper, D. (1988), "Flexibility in Manufacturing System: Definition and Petri-Nets Modeling", *International Journal of Production Research*, Vol. 26, No. 2, pp.237-248.

Barad, M. and Sipper, D. (1990), "Flexibility and Types of Changes in FMSs: A Timed Petri-Nets Assessment of Machine Flexibility", *The International Journal of Advanced Manufacturing Technology*, 5, pp.292-306.

Benjaafar, S. and Talavage, J. J. (1992a), "Axiomatic Measure of Flexibility in Advanced Manufacturing Systems, *1992 IEEE International Conference on Systems, Man and Cybernetics*, Vol. 2, #92CH3176-5.

Benjaafar, S. and Talavage, J. J. (1992b), "Process Flexibility in Manufacturing Systems: Models and Measurements", Working paper, School of Industrial Engineering, Purdue University, West Lafayette, IN, August.

Benjaafar, S., Morin, T. L. and Talavage, J. J. (1995), "The Strategic Value of Flexibility in Sequential Decision Making", *European Journal of Operational Research*, Vol., 82, pp. 438-457.

Brill, P. H., and Mandelbaum, M. (1989), "On Measurement in Manufacturing Systems", *International Journal of Production Research*, Vol. 27, No. 5, pp.747-756.

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P. and Stecke, K. E. (1984), "Classification of Flexible Manufacturing System", *The FMS Magazine*, 2 (2), pp.114-117.

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the 1st International Conference on FMSs*, Brighton, UK, pp.13-22.

Carter, M. F. (1986), "Designing Flexibility into Automated Manufacturing Systems", in *Proceedings of 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, pp. 107-118.

Chandra, P. and Tomback, M. M. (1992), "Models for the Evaluation of Routing and Machine Flexibility", *European Journal of Operations Research*", Vol., 60, pp.156-165.

Chang, A. Y. (1999), "Manufacturing Strategy Development for Small and Medium-Sized Companies in Taiwan", *Journal of National Huwei Institute of Technology*, Vol. 2, pp. 425~440.

Chang, A.Y., Whitehouse, D. J., Chang, S. L. and Hsieh, Y. C. (1998) "A Revised Entropy Approach to the Measurement of Manufacturing System Flexibility", in *Proceeding of the Joint Conference of The Fifth International Conference on Automation Technology (Automation 98') and 1998 International Conference of Production Research (Asia Meeting)*, Taipei, Taiwan, R.O.C.

Charnes, A., Cooper, W. W. and Rhodes, E. (1978), "Measuring the Efficiency of Decision Making Units", *European Journal of Operations Research*, 2, pp.429-444.

Chatterjee, A., Cohen, M. A., Maxwell, W. L. and Miller, L. W. (1984), "Manufacturing Flexibility: Models and Measurements", in *Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.49-64.

Chung, C. H. and Chen, I. J. (1989), "A Systematic Assessment of the Value of Flexibility from FMS", in *Proceedings of the Third ORSA/TIMS Special Interest Conference on FMS*, New York: Elsevier.

Chung, C. H. and Chen, I. J. (1990), "Managing the Flexibility of Flexible Manufacturing Systems for Competitive Edge", in M. J. Liberatore (Ed.), *Selection and Evaluation of Advanced Manufacturing Technologies*, Springer-Verlag, New York, pp.280-305.

Chung, C. H. and Chen, I. J. (1996), "An Examination of Flexibility Measurements and Performance of Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 34, no. 2, pp.379-394.

Das, S. K. (1996), "The Measurement of Flexibility in Manufacturing Systems", *The International Journal of Flexible Manufacturing Systems*, 8, pp.67-93.

Eilon, S. (1985), "A Framework for Profitability and Productivity Measures", *Interface*, Vol. 35, no. 3, June, pp.31-40.

Falkner, C. H. (1986), "Flexibility in Manufacturing Plant", in *Proceedings of 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, pp. 95-106.

Farrell, M. J. (1957), "The Measurement of Productive Efficiency", *Journal of the Royal Statistical Society A 120*, part 3, pp.253-281.

Forsund, F. R., Lovell, C. A. K. and Schmidt, P. (1980), "A Survey of Frontier Production Functions and of Their Relationship to Efficiency Measurement", *Journal of Econometrics*, Vol. 13, pp.5-25.

Gerwin, D. (1982), "Do's and Don'ts of Computerized Manufacturing", *Harvard Business Review*, Vol. 60, pp.107-116.

Gerwin, D. (1993), "Manufacturing Flexibility: A Strategic Perspective", *Management Science*, Vol. 39, No. 4, pp.395-410.

Golany, B. and Roll, Y. (1992), "Incorporating Standards via DEA", in A. Charnes, W. W. Cooper, A. Y. Lewin and L. M. Seiford (Ed.), *Data Envelopment Analysis: Theory, Methodology, and Application*, Kluwer Academic Publishers.

Greene, W. H. (1980), "Maximum Likelihood Estimation of Econometric Frontier Functions", *Journal of Econometrics*, Vol. 13, pp.27-56.

Gupta, D. (1993), "On Measurement and Evaluation of Manufacturing Flexibility", " *International Journal of Production Research*, Vol. 31, No. 12, pp.2947-2958.

Gupta, D. and Buzacott, J. A. (1989), "A Framework for Understanding Flexibility of Manufacturing Systems", *Journal of Manufacturing Systems*, Vol., 8, no. 2, pp. 89-97.

Gupta, Y. P. and Goyal, S. (1989), "Flexibility of Manufacturing Systems: Concepts and Measurements", *European Journal of Operational Research*, 43, pp.119-135.

Gustavsson, S. O. (1984), "Flexibility and Productivity in Complex Production Processes", *International Journal of Production Research*, Vol. 22, No. 5, pp.801-808.

Hutchinson, G. K. and Sinha, D. (1989), "Quantification of the Value of Flexibility," *Journal of manufacturing Systems*, Vol. 8, No. 1, pp. 47-56.

Hyun, J. H. and Ahn, B. H. (1992), "A Unifying Framework for Manufacturing Flexibility", *Manufacturing Review*, Vol. 5, No. 4, pp.251-260.

Jacquemin, A. P. and Berry, C. H. (1979), "Entropy Measure of Diversification and Corporate Growth", *The Journal of Industrial Economics*, Vol. 27, no. 4, June, pp.359-369.

Jaikumar, R. (1986), "Postindustrial Manufacturing", *Harvard Business Review*, Vol. 64, pp.69-76.

Kumar, V. (1986), "On Measurement of Flexibility in Flexible Manufacturing Systems: An Information Theoretic Approach", in *Proceedings 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, The Netherlands, pp.131-143.

Kumar, V. (1987), "Entropic Measurement of Manufacturing Flexibility", *International Journal of Production Research*, Vol. 25, No. 7, pp.957-966.

Masuyama, A (1983), "Idea and Practice of Flexible Manufacturing System of Toyota", *Proceedings of the 7th International Conference on Production Research*, Windsor, Ont., pp. 584-590.

Mandelbaum, M. and Brill, P. H. (1989), "Examples of Measurement of Flexibility and Adaptivity in Manufacturing Systems", *Journal of the Operational Research Society*, Vol. 40, No. 6, pp.603-609.

Meeusen, W. and Broeck, J. van den (1977), "Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error", *International Economic Review*, Vol. 18, no. 2, June, pp.435-444.

Palepu, K. (1985), "Diversification Strategy, Profit Performance and the Entropy Measure", *Strategic Management Journal*, Vol. 6, pp.239-255.

Primrose, P. L. and Leonard, R. (1986), "Conditions under Which Flexible Manufacturing Is Financially Viable", in *Proceedings of the 3rd International Conference on FMS*, FMS, KFS (Publications) Ltd.

Ramasesh, R. V. and Jayakumar, M. D. (1991), "Measurement of Manufacturing Flexibility: A Value Base Approach", *Journal of Operations Management*, Vol. 10, NO. 4, pp.446-468.

Richmond, J. (1974), "Estimating the Efficiency of Production", *International Economic Review*, Vol. 15, no. 2, June, pp.515-521.

Rumelt, R. P. (1974), *Strategy, Structure and Economic Performance*, Harvard University Press, Cambridge, MA.

Rumelt, R. P. (1982), "Diversification Strategy and Profitability", *Strategic Management Journal*, Vol. 3, pp.359-369.

Schmidt, P. (1976), "On the Statistical Estimation of Parametric Frontier Production Functions", *Review of Economics and Statistics*, Vol. 58, no. 2, May, pp.238-239.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Shannon, C. E. (1948), "A Mathematical Theory of Communication", *Bell System Technical Journal*, Vol. 27, pp.379-423, 633-659.

Skinner, W. (1974), "The Focused Factory", *Harvard Business Review*, May-June, p.113-121.

Slack, N. (1983), "Flexibility as a Manufacturing Objective", *International Journal of Production Management*, Vol. 3, No. 3, pp.4-13.

Slack, N. (1987), "The Flexibility of Manufacturing Systems", *International Journal of Production Management*, Vol. 7, No. 4, pp.35-45.

Slack, N. (1989), "Focus on Flexibility", in Wild, R. (Ed.), *International Handbook of Production and Operations Management*, Cassell Educational Ltd, London, pp.50-73.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advance Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Tincknell, D. J. and Radcliffe, D. F. (1996), "A Generic Model of Manufacturing Flexibility Based on System Control Hierarchies", *International Journal of Production Research*, Vol. 34, No. 1, pp.19-32.

Theil, H. (1967), *Economics and Information Theory*, North-Holland Publishing Company, Amsterdam, Netherlands.

Upton, D. M. (1994), "The Measurement of Manufacturing Flexibility", *California Management Review*, Winter, pp.72-89.

Upton, D. M. (1995), "What Really Makes Factories Flexible?", *Harvard Business review*, July-August, pp. 74-84.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows 2* (Special Issue on Flexible Manufacturing System), pp.143-149.

Chapter 5

Input-Orientated Flexibility Measurement

5.1 Introduction

Although flexibility has been recognized as a competitive weapon in international and domestic marketplaces, researchers are still confused in defining the meaning of manufacturing flexibility (Chung and Chen, 1990). Managers, moreover, are still unable to clearly understand how to implement it when they have to cope with an uncertain environment (Slack, 1989). In order to explain the confusion, Swamidass (1988) stated that three problems were caused in the literature, namely: (1) the overlapping in the concept, (2) aggregation of others into one term, and (3) identical terms with different meanings.

Researchers have tried to refocus the concepts of manufacturing flexibility; nevertheless, there still exists a lack of any comprehensive and integrated treatment on measurement of manufacturing flexibility. They are either incomplete or too abstract for operational applications; moreover, the measurements are somewhat too simple to cover the whole concept of flexibility or lack thorough consideration (Ettile, 1988; Sethi and Sethi, 1990; and Chung and Chen, 1996). Consequently, the understanding and suitable guidance for improving system performance when coping with uncertain environments are blurred. Hence this creates difficulties for a firm in setting up manufacturing flexibility as its competitive priority.

Overall, for the implementation of manufacturing flexibility at the operational level, an unambiguous understanding of the meaning of manufacturing flexibility and a holistic treatment are essential to both researchers and plant managers.

In this Chapter, Section 2 clarifies the concept of flexibility in manufacturing systems and makes an operational definition for its measurement. Section 3 examines the entropy approach and proposes a revised entropy approach. The algorithm of the revised approach and a straightforward example of machine flexibility measurement has been illustrated in Section 4. Section 5 proposes a more general model of the efficiency frontier approach, data envelopment analysis (DEA), for the evaluation of the system's efficiency, which will be incorporated into the flexibility measurement of the manufacturing system. The conclusion of this part of the research is given in section 6.

5.2 The concept and definition of flexibility in a manufacturing system

The confusions caused in the current literature of manufacturing flexibility may be due to the lack of recognition of the fact that the concept of flexibility is polymorphous, which was the point stated by Evans (1991).

Evans (1991) developed the meaning of flexibility on the strategic level with nine related terms, namely: adaptability, agility, corrigibility, elasticity, hedging, liquidity, malleability, plasticity, resilience, robustness and versatility; and three different senses, namely: yielding to pressure, capability for new situations and susceptibility of modification, for a conceptual analysis of flexibility. Although each term is related, but not equal, to the meaning of flexibility, this does not seem reasonable to add these terms to generate a complete flexibility.

These related terms and their senses enable us to inspect the meaning of flexibility in more detail and the research in this thesis is therefore encouraged to produce a suitable and feasible concept for applying to manufacturing systems. Without a comprehensive investigation into the meaning of the flexibility concept and an integrated treatment in measuring manufacturing flexibility, the measurement usually results in Upton's (1995) observation: '*Flexibility is very difficult to measure and, of course, difficult to improve*'.

To sum up the meaning of flexibility, stated by Evans (1991), we might be able to infer that each related term contains two abilities, one in terms of capability and the other in capacity. We therefore might be able to conclude that flexibility in a manufacturing system is also embodied in or consists of these two abilities. Capability, meaning how far a system can go, is defined as the scope, range or envelope of the states embodied in the tasks that a system can perform; whereas capacity, meaning how fast or how easy the system can go, in terms of time and cost, is defined as the efficiency of performing the states, either doing changeover arbitrarily between the states or completing a specific state.

By applying such a concept to measuring manufacturing flexibility, the meaning of economies of scope, which was proposed by Goldhar and Jelinek (1983), can therefore be examined. If the forms of two abilities are embodied in the concept of flexibility, we can argue that flexibility is depicting the meaning of economies of scope. It means that a manufacturing system is able efficiently, in terms of time and economy, to perform a wide variety of the tasks contained in the manufacturing system and its subsystems. Slack's (1983, 1989) definition came closest to the meaning of economies of scope. According to his definition, Slack pointed out that it is necessary to include not only the range of states a system can adopt, but also the ease of moving from one state to another, in terms of time and/or cost. Slack (1989) further explained the meaning of range as *'the total envelope of capacity or range of states which the operations system is capable of achieving'.* This implies the term versatility. **Therefore, versatility and efficiency could measure manufacturing flexibility. Versatility expresses the capability, whereas efficiency expresses the capacity, of the systems.** The relationships of the relevant factors of flexibility are summarized as follows:

$$\text{Flexibility} = f\,(\text{Capability, Capacity}) \tag{5.1}$$

$$\text{Capability} = f\,(\text{Range}) \;\rightarrow\; (\text{Versatility Measurement}) \tag{5.2}$$

$$\text{Capacity} = f\,(\text{Time, Cost}) \;\rightarrow\; (\text{Efficiency Measurement}) \tag{5.3}$$

Therefore,

$$\text{Flexibility} = \text{f}\,(\text{Versatility, Efficiency}) \tag{5.4}$$

$$= f\,(\text{Range, Time, Cost}) \tag{5.5}$$

Given this conclusion the thesis defines **the flexibility of a manufacturing system as a system which has the ability to perform a wide variety of activities with high efficiency.**

5.3 The entropy approach and its problem in flexibility measurement

The mathematical model of entropy approach and its properties, which have been explored in Chapter 4, will be quoted here as follows:

$$S(\rho_1, \rho_2, \ldots, \rho_n) = -\sum_{i=1}^{n} \rho_i \log \rho_i \tag{5.6}$$

where $0 \le \rho_i \le 1$ and $\sum \rho_i = 1$, $i=1,\ldots,n$.

The entropy function contains the following properties (Kumar, 1986):

(1) There is a continuous probability function of $\rho_1, \rho_2, \ldots, \rho_n$.

(2) This function should be at its maximum when $\rho_1 = \rho_2 = \ldots = \rho_n = 1/n$.

(3) The maximum value of this function should increase as n increases.

$$S(\rho_1, \rho_2, \ldots, \rho_n) = \log n \tag{5.7}$$ [1]

(4) The function should be at its minimum when one of the possibilities is unity and all other probabilities are zero and this minimum value of the function should be zero.

(5) The function should not change when an additional option with zero probability is allowed.

In Kumar's (1986, 1987) entropy method, he demonstrated that the more alternative decision options, the greater the value of entropy, i.e., the greater the flexibility. Such a consideration is the same as the range of the states; however, the method is required to incorporate the efficiency dimensions. This suggestion is consistent with Chandra and Tombak's (1992) examination of routing flexibility measurement. Chandra and Tombak (1992) have proved that the entropy approach, proposed by Kumar (1986, 1987), was not appropriate for the evaluation of the manufacturing flexibility measurement, as it did not incorporate reliability into the measurement model. The flexibility of a system should

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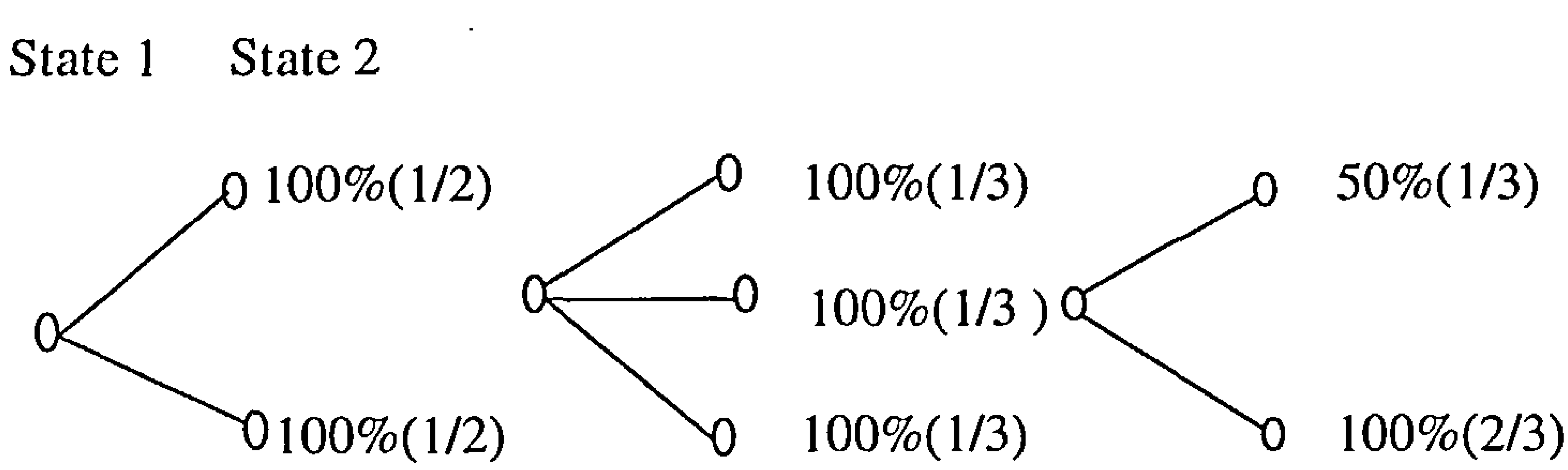
[1] [Prove] $S(\rho_i) = -\sum_{i=1}^{n} \rho_i \log \rho_i = -\sum_{i=1}^{n} \frac{1}{n} \log \frac{1}{n} = -n \times \frac{1}{n} \log \frac{1}{n} = \log n$

not be necessary monotonically increased with the number of alternatives. Reliability should at least another factor for the measurement of the manufacturing flexibility. A simple and straightforward example illustrates the shortcoming of the entropy approach as the following. Corea (1994) has also argued the problem of entropy approach to measure manufacturing flexibility.

Suppose two plants A and B both can produce three products, but, plant A can produce them in half the time and at half the cost of plant B. Obviously, plant A is more flexible than plant B. However, when we measure both of them by the entropy approach, they show exactly the same value. Moreover, if we take Kumar's (1986) example, depicted in Figure 5.1, it is clear that Case 2 is more flexible than Case 1 and Case 1 is more flexible than Case 3, if we apply the entropy approach to these three cases.



Case 1. Two Options, Equal Freedom   Case 2. Three Options, Equal Freedom   Case 3. Two Options, Unequal Freedom

Figure 5.1: Options and their freedom (Kumar, 1986)

However, if we add a Case 4, Figure 5.2, with two options and equal freedom but half the reliability compared with Case 1, we will see that (1) Case 4 has the same flexibility as Case 1, and (2) Case 4 shows more flexibility than case 3. The results with the entropy evaluation approach seem unreasonable.

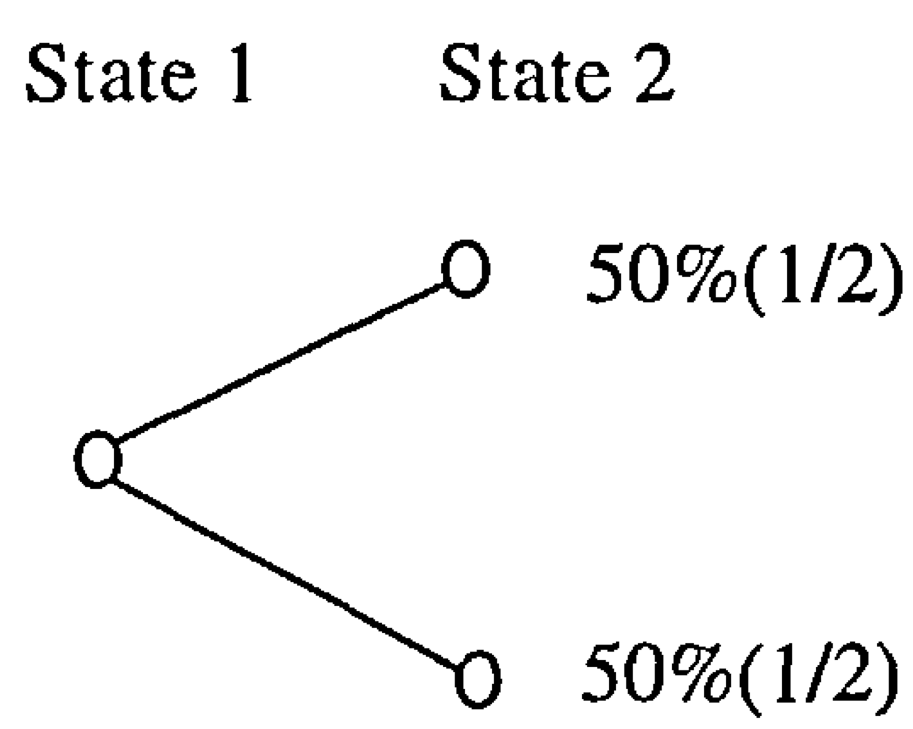


Figure 5.2: Additional option and its freedom

Slack (1989) argued that there is a need to consider the "ease" factor in terms of time and/or cost. With a more complete consideration, Benjaafar and Talavage (1992a, 1992b) embodied the "ease" element--efficiency--when measuring the flexibility. Upton (1995) asserted the same idea in measuring flexibility. He stated that increasing range in terms of the breadth of product characteristics a system could produce, increasing mobility in terms of changeover time, and achieving uniform performance in terms of cost, quality, or others, across a specified range, increase a system's flexibility. Unfortunately, they also fell into the same trap as Kumar (1986, 1987) did. **It would be reasonable to revise the entropy model to measuring manufacturing flexibility, by introducing the efficiency value *e* into equation (5.7) as a weighting factor.** Thus,

$$S(\rho_1, \rho_{2,\dots,}\rho_n) = -\sum_{i=1}^{n} e_i \rho_i \log \rho_i \tag{5.8}$$

By doing such a revision, we can conclude that the more efficient the systems perform, the greater the value of entropy and the degree of flexibility increase. Such a revised function will meet the above property (2) and reach the same maximum value as (6), when all e_is are unity. Nevertheless, the revised approach does not guarantee the function should increase as n increases, which is stated in the above property (3), unless the system can increase n with as high efficiency as in the original ones.

It seems reasonable that when a firm increases its product breadth, that is - introduce new products to the system, it might lower the system's performance dramatically because of adapting to the new situation. Hence, **the revised entropy approach seems a more reasonable expression of the characteristics of flexibility of manufacturing systems**. For explaining the revised approach, a straightforward algorithm and example are illustrated in the following section.

5.4 An illustration of a single machine flexibility measurement

5.4.1 Productive performance

A flexible system contains the ability to produce a wide range of *states* on its particular *task* with high efficiency. Here the *state* means the outcome of the performance, which may comprise a number of parameters, in terms of quantity, time, cost, reliability, quality and availability etc. It depends on the characteristics of the system or the requirements of management.

For simplifying the illustration of the revised entropy approach, this research takes the machine as the evaluation object for the measurement. Suppose that there are n operations which can be performed by m machines in a system. The productive matrix can be obtained as Figure 5.3, where the o_{ij} represents the productive performance of machine j on performing operation i. It may be the outputs of operation i per hour performed by machine j.

$$\begin{array}{c} \\ O_1 \\ O_2 \\ \vdots \\ \vdots \\ O_n \end{array} \begin{array}{c} \begin{array}{cccc} M_1 & M_2 & \cdots\cdots & M_m \end{array} \\ \begin{bmatrix} O_{11} & O_{12} & \cdots\cdots & O_{1m} \\ O_{21} & O_{22} & \cdots\cdots & O_{2m} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ O_{n1} & O_{n2} & \cdots\cdots & O_{nm} \end{bmatrix} \end{array}$$

Figure 5.3: Productive performance matrix

5.4.2 Efficiency computation

A general model for evaluating the efficiency of a system will be discussed in the next section. In this section, in order to illustrate the revised entropy approach we use a simpler method to evaluate the efficiency of the machines. The efficiency of machine j on performing operation i, e_{ij}, is to compare the output of machine j on performing the operation i to the maximum output of the machine which can produce the same operation i in the system. Hence, e_{ij} can be described as (5.9).

$$e_{ij} = \frac{o_{ij}}{\sum_{j \in J} o_{ij}} \tag{5.9}$$

where $0 \le e_{ij} \le 1$ and J is the set of machines in the system. The efficiency matrix is illustrated as Figure 5.4.

$$
\begin{array}{c}
 \\ O_1 \\ O_2 \\ \vdots \\ \vdots \\ O_n
\end{array}
\begin{array}{c}
\begin{array}{cccccc} M_1 & M_2 & \cdots & \cdots & M_m \end{array} \\
\begin{bmatrix}
e_{11} & e_{12} & \cdots & \cdots & e_{1m} \\
e_{21} & e_{22} & \cdots & \cdots & e_{2m} \\
\vdots & \vdots & & & \vdots \\
\vdots & \vdots & & & \vdots \\
e_{n1} & e_{n2} & \cdots & \cdots & e_{nm}
\end{bmatrix}
\end{array}
$$

Figure 5.4: The efficiency matrix

5.4.3 Normalization procedure

For obtaining the entropy approach's properties, the efficiency matrix is required to transfer into a matrix with unity column, in which each column should add up to unity. It can be used by (5.10) to normalize the matrix.

$$\rho_{ij} = \frac{e_{ij}}{\sum_{i=1}^{n} e_{ij}} \tag{5.10}$$

where, $0 \le \rho_i \le 1$, i =1,...,n, j = 1, ..., m, and $\sum \rho_i = 1$. A normalized efficiency matrix can be shown as Figure 5.5.

$$
\begin{array}{c}
 \\ O_1 \\ O_2 \\ \vdots \\ \vdots \\ O_n
\end{array}
\begin{array}{c}
\begin{array}{cccccc} M_1 & M_2 & \cdots & \cdots & M_m \end{array} \\
\begin{bmatrix}
\rho_{11} & \rho_{12} & \cdots & \cdots & \rho_{1m} \\
\rho_{21} & \rho_{22} & \cdots & \cdots & \rho_{2m} \\
\vdots & \vdots & & & \vdots \\
\vdots & \vdots & & & \vdots \\
\rho_{n1} & \rho_{n2} & \cdots & \cdots & \rho_{nm}
\end{bmatrix}
\end{array}
$$

Figure 5.5: Normalized efficiency matrix

5.4.4 Flexibility computation

By incorporating efficiency evaluation in measuring manufacturing flexibility, the proposed formulation model is as follows:

$$\Phi(F_{.j}) = -\sum_{i=1}^{n} e_{ij}\rho_{ij}\log\rho_{ij} \tag{5.11}$$

5.4.5 A numerical illustration

This section demonstrates machine flexibility with the proposed approach. Consider a factory, which has 4 machines performing 3 operations. The correspondent table of the output units per hour is as shown in Table 5.1. Consequently, the efficiency table, the normalized efficiency table, and the machine flexibility table can be shown as in Table 5.2, Table 5.3 and Table 5.4, respectively.

Table 5.1: The output per hour of machine and operation

	M_1	M_2	M_3	M_4
O_1	80	90	100	40
O_2	80	60	70	40
O_3	80	90	70	40

Table 5.2: Efficiency table

	M_1	M_2	M_3	M_4
O_1	0.8	0.9	1	0.4
O_2	1	0.75	0.875	0.5
O_3	0.889	1	0.778	0.444

Table 5.3: Normalized efficiency table

	M_1	M_2	M_3	M_4
O_1	0.297	0.340	0.377	0.298
O_2	0.372	0.283	0.33	0.372
O_3	0.331	0.377	0.293	0.33

Table 5.4: Machine flexibility table

Flexibility	M_1	M_2	M_3	M_4
REA	0.426	0.419	0.42	0.213
EA	0.475	0.474	0.475	0.475

In Table 5.4, REA and RA represent the flexibility value calculated by the revised entropy approach and the entropy approach, respectively. The table shows that machine 1 is the most flexible in all, although it produces the same amount of outputs per hour as the other two machines, 3 and 4. The reason is that machine 1 performs three operations with more uniformity. However, Table 5.4 also shows that machine 4 has the same flexibility value as machine 1 with the entropy approach, although the output per hour of machine 4 is half that of machine 1 and it shows more flexibility than machines 2 and 3. This is intuitively unreasonable. The maximum value of the example is $log\ n = log\ 3 = 0.477$. The REA seems more sensible as a means of depicting the flexibility value.

5.4.6. Efficiency measurement

By using the efficiency factor in the revised entropy approach, the method for evaluating the efficiency of the system will be of great importance in the present research.

Son and Park (1987) proposed the flexibility measurement with the same concept as productivity. They measured equipment flexibility, process flexibility, product flexibility and volume flexibility with idle cost, waiting cost, setup cost and inventory cost to divide the total output respectively. The method proposed by Son and Park (1987) is related to the efficiency measurement with cost aspect, i.e., cost-efficiency consideration. However, Slack (1989) stated that the ease of making the changes from one state to the others contains not just cost but time also. In most cases, time and cost have their trade-off and time might be more important than cost. Obviously, Son and Park (1987) did not include versatility considerations in their model. Their suggestion might be reasonable for a job shop, which is required to produce medium- or low- volume with medium- or high-variety of products. The system will show more flexibility, if it incurs lower costs for achieving the changes with the same outputs. However, if we consider a mass production system, the model does not seem reasonable for depicting the flexibility of the systems.

As stated in the present research, efficiency is depicted in terms of time and cost. Chung and Chen (1990) proposed the same viewpoint when they examined the total system flexibility (*TSF*) with two conceptual schemes, emboding the quickness of response to a change (Q) and economic response to the change (E), i.e., time and cost dimensions. The two conceptual schemes are:

$(a)TSF = \alpha Q + (1-\alpha)E$, where, $0 \leq \alpha \leq 1$ (5.12)

$(b)TSF = Q^{\alpha} E^{\beta}$, where $\alpha + \beta = c$ and $c \geq 1$ is a constant (5.13)

These two schemes obviously did not entirely characterize the requirements of measuring flexibility. They failed to measure versatility in their schemes. Consequently, Their point of view is against Zelenovic (1982) and Gustavsson's (1984) conclusions.

The reason why Chung and Chen (1990) came to this conclusion is that they defined flexibility using only time and cost dimensions, which are only suitable for efficiency evaluation. They lack a consideration of versatility as well. Certainly, as long as a system can improve its efficiency in terms of time and cost, it will increase its productivity; however, for increasing versatility, the answer may be yes, may be no. Although (5.12) and (5.13) are good indications on measuring efficiency, this research would apply an efficiency frontier approach for evaluating the efficiency of a system.

5.4.7 Efficiency frontier approach - The DEA model application

As concluded in the Chapter 3, Gupta and Goyal's (1989) viewpoint has been adopted that time and cost are inversely related and are considered as the efficiency factors.

In Figure 5.6 the T_i, C_i, *and* O_i (i=1,...,n) represent the *time*, *cost*, and *output* of the system respectively, when the system performs the i^{th} *state* (*range*) of the *task, i.e,. Time* and *cost* are input variables and *output* is an output variable of the DEA model. If we take "return to scale" as the assumption, the model can only take unit production time and unit production cost as input variables and there is no need to consider the output variable. When incorporated into the revised entropy approach of versatility measurement, such a consideration meets Slack (1989) and Gerwin's (1993) suggestions.

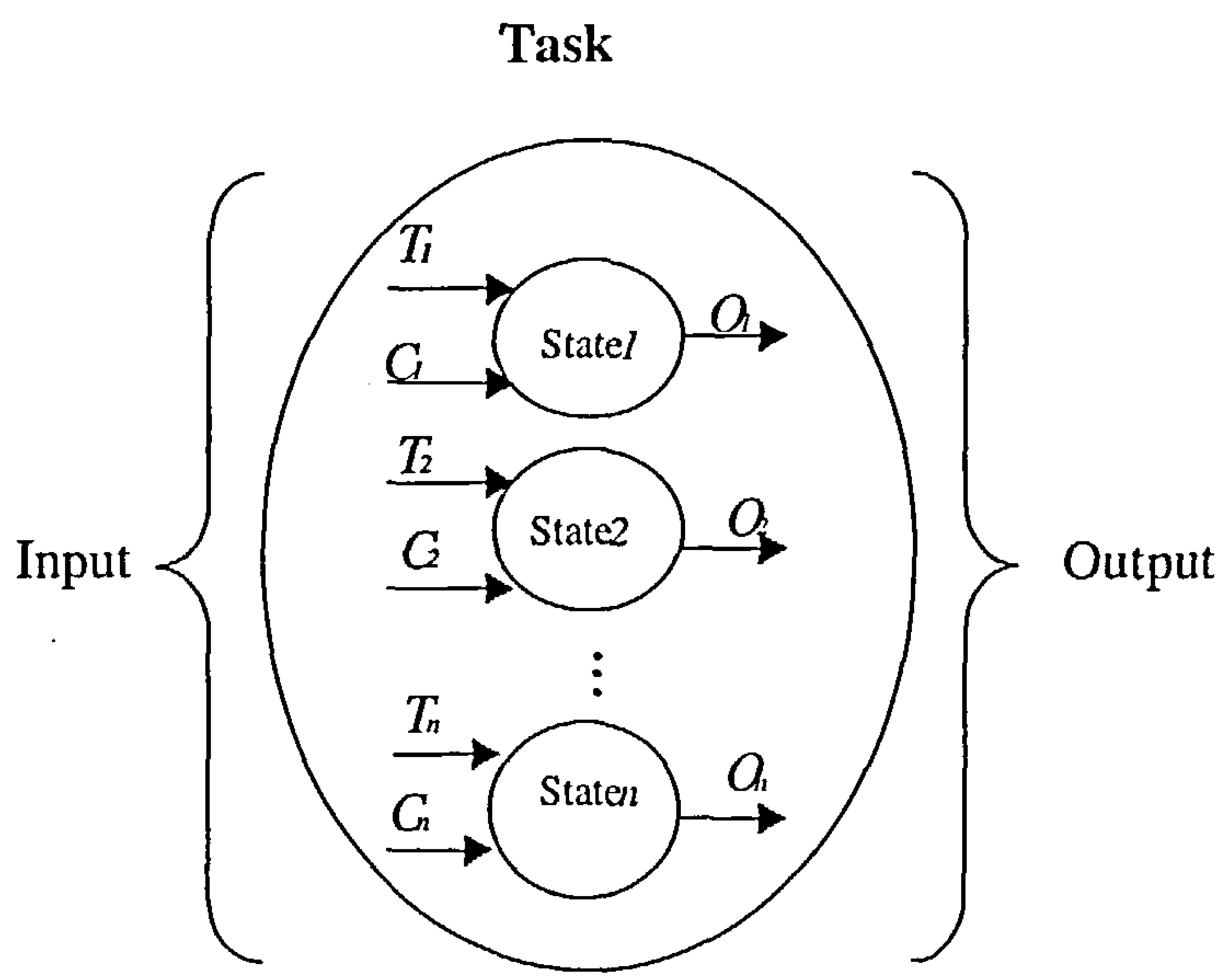


Figure 5.6: The efficiency measurement framework

This research proposed that the measurement of manufacturing flexibility should take into account the versatility and efficiency evaluation simultaneously. The entropy approach is a good method for the measurement of versatility; however, there is an additional requirement to include efficiency for the manufacturing flexibility measurement. The DEA approach, which is derived from the production frontier approach, is a promising method for evaluating the efficiency of a system.

Provided that the range, i.e., type, volume, kind, frequency, and so forth, of the outputs of a system can be specified and the whole efficiency values of the outputs can be evaluated, the flexibility of the system, consequently, can be obtained by the revised entropy approach.

The application procedure could be summarized as the following:

1. Define the *task* of the evaluating system;
2. Identify the *range* of the different *states*, containing in the *task*, performed by the system;
3. Evaluate the *efficiency* value for the states respectively by comparing to the best practice of the peer group with the DEA approach;
4. Normalize the efficiency values of the task into a unity vector for the application of entropy approach, *versatility* evaluation; and
5. Calculate the flexibility of the system by the revised entropy approach model.

5.5 Group machine flexibility measurement

5.5.1 Introduction

The approaches proposed in the literature seem to lack a clear description of how to distinguish between single machine flexibility and group machine flexibility. It appears unreasonable to take group machines as a whole system and evaluate the system flexibility by looking into the range of different output tasks or the changeover effectiveness of different operations. Just like the evaluation of a system's routing flexibility, it should take the concept of redundancy into consideration, e.g., machines are able to take over the operations when one of the occupied machines breaks down, meaning alternative routes for the production of a part or product.

Single machine flexibility measurement has been proposed by Brill and Mandelbaum (1989), Mandelbaum and Brill (1989), Brill and Mandelbaum (1990), Das (1996), and Chung and Chen (1996). They all supposed that the efficiency values of the measured system were given. However, it can be complicated to evaluate the efficiency value of a system in performing a task. It is therefore necessary to examine the efficiency value in more detail. Efficiency alone has its limitation in depicting the flexibility of a system (Chang et al., 1998). Versatility at least should be an another important factor for the measurement of single machine flexibility. Moreover, it is necessary to have redundant resources in terms of capacity, capability or utilization to guarantee the job can be done within the planned schedule (Slack, 1989; Correa, 1994).

Extra factors, such as weight of importance, could be added to the measurement models, when it is necessary to managers to set up their effective competition. However, such a consideration will make the efficiency value a relative concept and hard to compare with different systems or at different times.

5.5.2 Literature review

Brill and Mandelbaum (1989) proposed that the approach of measuring the flexibility of a machine group is to sum up the weighted effectiveness of performing the output tasks and further take the mean value of the total weighted effectiveness. The approach proposes the factor of efficiency as one element of flexibility. However, it lacks a detailed consideration on versatility evaluation, although it has inherently appeared in their model. The model of a machine flexibility ($F_{i,T}$) they proposed is as follow. Let e_{ij} denote the efficiency value of machine i for doing task j, where $0 \le e_{ij} \le 1$.

$$F_{i,T} = \frac{\sum_{j \in T} e_{ij} w_j}{\sum_{j \in T} w_j} \tag{5.14}$$

where w_j denotes the weight of importance of task j, $0 \le w_j \le 1$. T represents a subset of all tasks T and $\sum_{j \in \mathrm{T}} w_j = 1$, therefore, $0 < \sum_{j \in T} w_j \le 1$.

The problem is that they summed up the importance weights of the tasks as unity. The viewpoint proposed in the present research suggests that each weight for the task should be constrained within the range of 0 to 1 and it is not necessary to sum up the total value of the weights as 1. Take the following example. Suppose that machine A can perform 3 operations all with efficiency 0.8, while machine B can only perform 2 of 3 above also with efficiency 0.8. Referring to Brill and Mandelbaum's (1989) approach, the two machines above show equal flexibility with the same value 0.8, if the important weights have been set as equal and summed up to unity. This is obviously misleading.

Chen and Chung (1996) illustrated two types of single machine flexibility namely unweighted machine flexibility and weighted machine flexibility. The former is actually a versatility consideration, while the latter adopted the approach of Brill and Mandelbaum (1989) and took away the denominator of function (5.14). The weights of importance, proposed by Chen and Chung (1996), refer to the frequency of the operation required for completing a set of part types. Moreover, they evaluate the operation efficiency with the length of operation processing time only, although they suggested that setup time, processing cost, processing quality, etc. could be incorporated into the measurement model.

Quoted from Brill and Mandelbaum's (1989) approach, Das (1996) excluded the weights as the measurement of machine flexibility. Moreover, Das (1996) introduced limiting efficiency to set constraints for the evaluation model. Das's (1996) approach excludes the very low values of efficiency, because it is unlikely that the operations will be assigned to inefficient machines. Such constraints seem to have limitations. Some operations will occasionally be assigned to the low efficiency machines, when the other higher efficiency machines have been occupied by the other operations or broken down for some reason. It could be more reasonable to regard flexibility as an intrinsic capability.

Chang et al. (1998) defined flexibility of a system as the effectiveness of performing a wide range of tasks. They illustrated the single machine flexibility model with two basic factors, namely efficiency and versatility. In their proposed approach, they combined these two factors into a revised entropy model. It appears to be more sensible way to depict the concept of manufacturing flexibility. The idea could be expanded to the measurement of group machine flexibility measurement, as there are different attributes between single machine and group machines when considering the flexibility measurement (Gupta, 1993).

5.5.3 Measurement approach

In order to develop the measurement models, a general matrix is illustrated as Table 5.5 to show the relationship between systems and tasks. Suppose that there are m systems all having the ability to perform n tasks. The element in the matrix represents the task efficiency value, ranged from 0 to 1, performed by the corresponding system. With such a matrix, the factors of flexibility in terms of efficiency, versatility and redundancy will be demonstrated respectively.

Table 5.5: A general resource group flexibility measurement

Task (T_j)		T_1	T_2	T_3	...	T_n	Versatility (V)
Weights(W)		W_1	W_2	W_3	...	W_n	
System (S_i)	S_1	e_{11}	e_{12}	e_{13}	...	e_{1n}	$f(S_1)$
	S_2	e_{21}	e_{22}	e_{23}	...	e_{2n}	$f(S_2)$
	S_3	e_{31}	e_{32}	e_{33}	...	e_{3n}	$f(S_3)$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	...	$\vdots$	$\vdots$
	S_m	e_{m1}	e_{m2}	e_{m3}	...	e_{mn}	$f(S_m)$
Redundancy (R)		$f(T_1)$	$f(T_2)$	$f(T_3)$	...	$f(T_n)$	

Theoretically, a system is designed for producing specific types of output. The system can therefore perform those specific types of output with the most efficient ability. Nevertheless, when the system produces other types of *state*, or expands the *range* of *states*, the efficiency will be reduced, namely, increasing *cost* and *time* to produce the equal amount of the *state* output, or decreasing the amount of output with the same amount of *cost* and *time*. Therefore, **the changeover during the *states* theoretically decreases the efficiency.**

In practice, if a system can reduce the increased cost and time of the changeover as much as possible, the system will be able to maintain its original high efficiency. Therefore, if the range of states can be expanded by reducing the deficiency when switching to perform the states, the system increases its flexibility.

An efficiency measurement framework is depicted in Figure 5.7. Figure 5.7 illustrates the requirement of input and output variables for the measurement model which will rate the efficiency of a system *i* when performing the state *j*, denoted as S_{ij}. The viewpoint is adopted from Chen and Chung (1996) and Brill and Mandelbaum's (1989) suggestion that the efficiency evaluation of a system may consider the factor of quality.

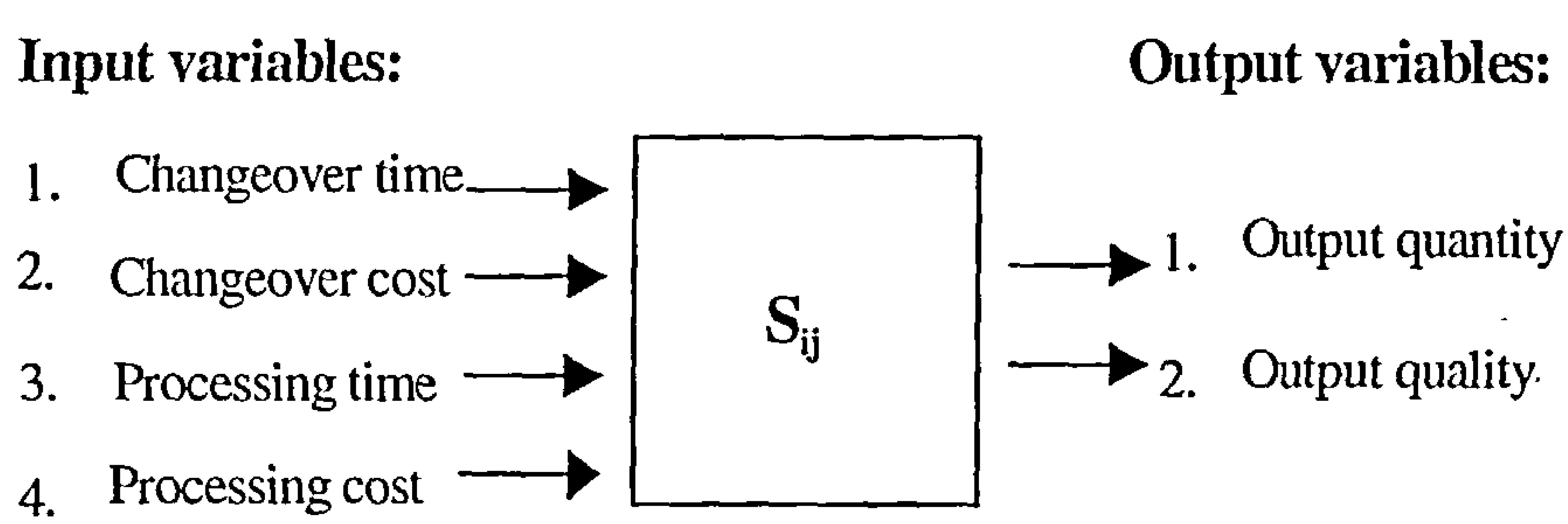


Figure 5.7: Variables description of the DEA model

5.5.4 Versatility and redundancy measurement of machine groups

In order to specify the model of group machine flexibility, the versatility measurement of a single machine and the redundancy of a single operation should be specified first.

5.5.4.1 Single machine versatility measurement

Versatility measurement needs to consider the number of output tasks performed by the evaluated system. One of the elements of the measurement model should be the greater the number of the tasks, the greater the flexibility of the system. Another element is to take into account whether the system can perform the tasks evenly well or not. The entropy approach, proposed by Shannon (1948) and which has been applied to the measurement of manufacturing system flexibility in the forms of routing flexibility and operation flexibility by Kumar (1986, 1987) and Yao (1986), fits well for such considerations, but is not properly applied to flexibility measurement (Chandra and Tombak, 1992; Correa, 1994; and Chang et al., 1998).

$$v_i = f(S_i) = -\sum_{j=1}^{n} \alpha_{ij} \log \alpha_{ij} \tag{5.15}$$

where

$$\alpha_{ij} = \frac{e_{ij}}{\sum_{j=1}^{n} e_{ij}} \tag{5.16}$$

and, e_{ij}, $0 \le e_{ij} \le 1$, is the machine-task effectiveness and efficiency of doing the operation j by machine i.

Equation (5.15) has following constraints:

(1) The function should increase with an increase of performed operations by the machine i, and

(2) The function should increase with the equally distributed efficiency values of the tasks performed by the machine i.

5.5.4.2 Single operation redundancy measurement

Redundant resources in the forms of capability, capacity or utilization are necessary to keep the system running, as it ensures the high efficiency of the system. Therefore, it is imperative to consider the number of redundant machines for the operations.

The concept of the entropy approach depicted above is also suitable for applying to the redundancy measurement of a system. The measurement model should consider the number of machines which are able to perform the same operations, and to examine if those machines can produce them evenly well in the system.

$$r_j = f(T_j) = -\sum_{i=1}^{m} \beta_{ij} \log \beta_{ij} \tag{5.17}$$

where

$$\beta_{ij} = \frac{e_{ij}}{\sum_{i=1}^{m} e_{ij}} \tag{5.18}$$

Equation (5.17) satisfies the following requirements:

(1) The function should increase with an increase in the number of machines which are able to perform the particular operation j.

(2) The function should increase with the equally distributed efficiency values of the operation j performed by those machines.

5.5.4.3 Group machine versatility measurement

The approach for the measurement of group machine versatility is, firstly, to take into account the number of operations, which are performed by the machine group, secondly, to consider the entropy value of each operation, and, thirdly, the redundant ability for performing the operations.

$$V = -\sum_{j=1}^{n} \gamma_j \log \gamma_j \tag{5.19}$$

where

$$\gamma_j = \frac{r_j}{\sum_{j=1}^{n} r_j} \tag{5.20}$$

Equation (5.19) have the following constraints:

(1) The function should increase with an increase in the number of operations performed by the group machine, and

(2) The function should increase with the increase in the uniformity of the entropy values.

5.5.4.4 Group machine redundancy measurement

The measurement of group machine redundancy needs to take into account the number of machines in the system, their entropy values for performing the operations and the versatile ability of the machines.

$$R = -\sum_{i=1}^{m} \sigma_i \log \sigma_i \tag{5.21}$$

where

$$\sigma_i = \frac{v_i}{\sum_{i=1}^{m} v_i} \tag{5.22}$$

Equation (5.21) have the following constraints:

(1) The function should increase with the increase in the number of machines in the system, and

(2) The function should increase with the increase in the uniformity of the entropy values of the machines.

5.5.5 Machine group flexibility measurement

The basic factors for the measurement of group machine flexibility has been illustrated in terms of efficiency, versatility and redundancy above. The following work for the measurement is to combine those three factors into a mathematical model for the measurement of machine group flexibility.

The configurations of machine group flexibility should concern, firstly, its effectiveness in performing the set of operations assigned to the machine group, secondly, the number of operations that the machine group can process, thirdly, the number of versatile machines in the group that can be substituted when unexpected interruptions occurred. Equation (5.23) includes these configurations.

$$F(MG) = \bar{e} \times V \times R \tag{5.23}$$

where $\bar{e}$ denotes the average efficiency values of the operations performed by the machines in the group. Therefore,

$$\bar{e} = \frac{1}{n \times m} \sum_{i=1}^{m} \sum_{j=1}^{n} e_{ij} \tag{5.24}$$

Equation (5.23) has at least the following constraints:

1. The function should increase with the increase in machine-operation efficiency values,
2. The function should increase with the increase in performed operations,
3. The function should increase with the increase in individual machine versatility,
4. The function should increase with the increase in redundant machine for the operations,
5. The function should increase with the increase in entropy values of each operation,
6. The function should increase with the increase in entropy values of each machine,

7. The function should increase with the greater uniformity of operation entropy values,
8. The function should increase with the greater uniformity of machine entropy values.

5.5.4 Example illustration

Table 2, adopted from Brill and Mandelbaum (1989), will be the example to illustrate the application to the models developed in the present research. However, the weights of importance will not be included in the illustration. It is possible to consider further such an additive factor into the models developed in the present research.

In Table 5.6, the row of redundancy (r_j) and the column of versatility (v_i) have been calculated with the model developed in this research. Following these results, the redundancy (R) and versatility (V) of the system could consequently be calculated as 0.776 and 0.768 with equation (5.19) and (5.21) respectively. The mean value of machine-task efficiencies in the matrix is 0.33, calculated with equation (5.24). Therefore, from the equation (5.23), the flexibility of the machine group is 0.197.

The use of the example above is not intended to compare this research with Brill and Mandelbaum's (1989) or other approaches. Rather, the research in this thesis demonstrates that a more comprehensive consideration of measuring machine group flexibility has been proposed and examined. This research asserts that at least three basic factors need to be combined together for measuring group flexibility.

Table 5.6: Machine flexibility measurement

Tasks	Machine-task efficiencies						Machine flexibility F_{mc_i}	Group machine flexibility	Machine versatility (v_i)
	1	2	3	4	5	6			
Weights of importance	0.1	0.1	0.2	0.2	0.4	0.0			
Group 1 machines mc_1	0.9	0.9	0	0	0	0	0.18	0.92	0.30
mc_2	0.7	0.6	0.5	0.3	0	0	0.29		0.583
mc_3	0	0	0.9	0.8	0.6	0	0.58		0.472
mc_4	0	0	0	0	1	0	0.40		0
Group 2 machines mc_5	1	1	1	1	1	1	1.00	1.0	0.778
Group 3 machines mc_6	0.5	0.3	0.4	0.7	0.8	0.9	0.62	0.62	0.604
mc_7	0	0	0.2	0.3	0.3	0	0.22		0.47
mc_8	0	0	0	0	0	0.9	0		0
Operation redundancy (r_j)	0.589	0.565	0.641	0.653	0.668	0.476			

5.6 Concluding Remarks

A brief review of the approaches, which have been applied in the measurement of machine and machine group flexibility, is given in Figure 5.8.

Researchers agree that flexibility in the manufacturing system is complicated and has inherent multi-dimensional characteristics. It is therefore difficult to measure. The research in this thesis inspects the flexibility concept thoroughly and fundamentally, and consequently proposes an operational definition of manufacturing flexibility as a form of measurement.

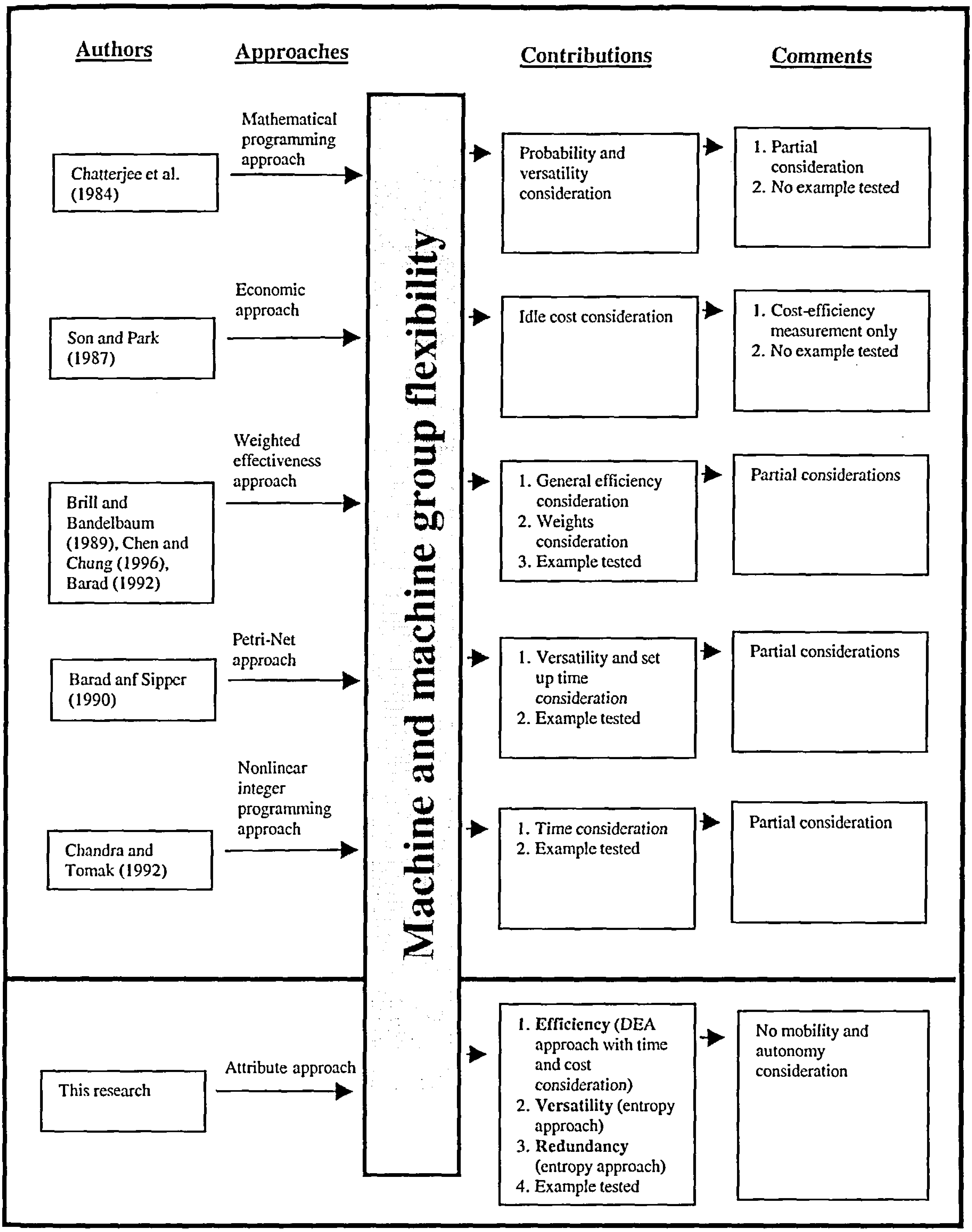


Figure 5.8: A brief review of machine & machine group flexibility measurement

The entropy approach proposed by Kumar (1986, 1987) shows the limitations applying to the measurement of manufacturing flexibility, although it has been widely applied to the measurement of uncertainty, economics, and markets etc., due to the lack of considering the factor of efficiency. To remedy the defect of the entropy approach, this research incorporates the efficiency element into the model as a revised entropy approach, which seems more reasonable in depicting the measurement of manufacturing flexibility.

Despite the application of this research to single machine flexibility, the revised approach could be expanded to the aggregate machine system, which is another advantage of the entropy approach. It could also be applicable to the other flexibility types of the manufacturing system, as long as the efficiency of the system or subsystem could be measured when they are performing the specific state of the task. For example, routing flexibility, if the number of routes for a part has been counted and each route efficiency has been evaluated, it is also measurable by the revised entropy approach.

The efficiency measurement could be relaxed to consider that time and cost have their different weighted importance: time, in particular, is getting more important than cost in the emerging competitive marketplace. Therefore, the DEA can be relaxed to consider weighted input variables.

The present research indicates that **the measurement of machine group flexibility should take into account three basic factors, namely efficiency, versatility and redundancy.** The measurement models for those three factors have been proposed. The combined measurement model for group machine flexibility has also been demonstrated.

Moreover, constraints associated with the models have been specified to examine if the model corresponds to the factors concept.

Efficiency for a system is actually quite a complicated concept. It should take multi-dimensional factors into consideration for the measurement model. This research therefore suggested the DEA as a tool for the evaluations. The DEA, **which is a linear programming based approach**, has been widely applied to the non-profit sectors and developed with commercial software. It is likely to be accepted and simple to operate in industry. The approach for the measurement of versatility and redundancy suggested in this thesis is adapted from the entropy method. **It ensures that the greater the options available the higher is the system entropy value.**

Other additive attributes, such as weight of importance and probability assignment to the occurrence of the tasks, could be added to the models for the system's competitive considerations. Consequently, the evaluation of *weighted flexibility* and *expected flexibility* of the system could be of interest to managers and are worth exploring in more detail.

5.7 References

Barad, M. and Sipper, D. (1988), "Flexibility in Manufacturing System: Definition and Petri Nets Modeling", *International Journal of Production Research*, 26(2), pp.237-248.

Benjaafar, S. and Talavage, J. J. (1992a), "Axiomatic Measure of Flexibility in Advanced Manufacturing Systems", 1992 *IEEE International Conference on Systems, Man and*

Cybernetics, Vol. 2, #92CH3176-5.

Benjaafar, S. and Talavage, J. J. (1992b), "Process Flexibility in Manufacturing Systems: Models and Measurements", Working paper, School of Industrial Engineering, Purdue University, West Lafayette, IN, August.

Brill, P. H., and Mandelbaum, M. (1989), "On Measurement in Manufacturing Systems", *International Journal of Production Research*, Vol. 27, No. 5, pp.747-756.

Brill, P. H., and Mandelbaum, M. (1990), "Measurement of Adaptivity and Flexibility in Production Systems", *European Journal of Operational Research*, 49, pp.325-332.

Chandra, P. and Tombak, M. M. (1992), "Models for the Evaluation of Routing and Machine Flexibility", *European Journal of Operations Research*, Vol., 60, pp156-165.

Charnes, A., Cooper, W. W. and Rhodes E. (1978), "Measuring the Efficiency of Decision Making Units", *European Journal of Operations Research*, 2, pp.429-444.

Chen, I. J. and Chung, C. H. (1996), "An Examination of Flexibility Measurements and Performance of Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 34, no. 2, pp.379-394.

Chung, C. H. and Chen, I. J. (1990), "Measuring Flexibility of Flexible Manufacturing Systems for Competitive Edge", in *Selection and Evaluation of Advanced Manufacturing Technologies*, M. Liberatore (ed.) (Berlin: Springer-Verlag), pp.280-305.

Correa, H. L. (1994), *Linking Flexibility, Uncertainty and Variability in Manufacturing Systems*, Avebury, Ashgate Publishing Limited, England.

Das, S. K. (1996), "The Measurement of Flexibility in Manufacturing Systems", *The International Journal of Flexible Manufacturing Systems*, 8, pp.67-93.

Ettile, J. E. (1988), *Implementation strategies for discrete parts manufacturing technologies: Final NSF Report*, University of Michigan (Ann Arbor, MI: University of Michigan).

Evans, J. S. (1991), "Strategic Flexibility for High Technology Maneuvers: A Conceptual Framework", *Journal of management Studies*, Vol. 28. no. 1, January, pp.69-89.

Farrell, M. J. (1957), "The Measurement of Productive Efficiency", *Journal of the Royal Statistical Society A* 120, part 3, pp.253-281.

Gerwin, D. (1993), "Manufacturing Flexibility: A Strategic Perspective", *Management Science*, Vol. 39, no. 4, pp.395-410.

Goldhar, J. D. and Jelinek, M. (1983), "Plan for Economies of Scope", *Harvard Business Review*, Nov.-Dec., pp.88-94.

Gupta, D. (1993), "On Measurement and Evaluation of Manufacturing Flexibility", " *International Journal of Production Research*, Vol. 31, No. 12, pp.2947-2958.

Gupta, Y. P. and Gyoal, S. (1989), "Flexibility of Manufacturing Systems: Concepts and Measurements", *European Journal of Operational Research*, 43, pp.119-135.

Gustavsson, S. O. (1984), "Flexibility and Productivity in Complex Production Processes", *International Journal of Production Research*, Vol. 22, no. 5, pp.801-808.

Kumar, V. (1986), "On Measurement of Flexibility in Flexible Manufacturing Systems: An Information Theoretic Approach", *Proc. 2Nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, pp.131-143.

Kumar, V. (1987), "Entropic Measurement of Manufacturing Flexibility", *International Journal of Production Research*, Vol. 25, no. 7, pp.957-966.

Mandelbaum, M. and Brill, P. H. (1989), "Examples of Measurement of Flexibility and Adaptivity in Manufacturing Systems", *Journal of the Operational Research Society*, Vol. 40, No. 6, pp.603-609.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Shannon, C. E. (1948), "A Mathematical Theory of Communication", *Bell System Technical Journal*, Vol. 27, pp.379-423, 633-659.

Slack, N. (1983), "Flexibility as a Manufacturing Objective", *International Journal of Production Management*, Vol. 3, no. 3, pp.4-13.

Slack, N. (1989), "Focus on Flexibility", in Wild, R. (Ed.), *International Handbook of Production and Operations Management*, Cassell Educational Ltd, London, pp.50-73.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advance Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Swamidass, P. M. (1988), "Manufacturing Flexibility", Monograph No. 2, Operation Management Association, January.

Upton, D. M. (1995), "What Really Makes Factories Flexible?", *Harvard Business Review*, July-August, pp. 74-84.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows 2* (Special Issue on Flexible Manufacturing System), pp.143-149.

Zelenovic, D. M. (1982), "Flexibility--A Condition for Effective Production Systems", *International Journal of Production Research*, Vol. 20, no. 3, pp.319-337.

Chapter 6

Process-Orientated Flexibility Measurement

6.1 Introduction

In this chapter the flexibility attributes are applied to process-orientated flexibility. The types of flexibility in this area, defined by the present research, are process flexibility, routing flexibility, programme flexibility and operation flexibility. The first two types of flexibility are the ones chosen for the application, because they seem to be more important than the last two, according to the frequency with which these two groups of flexibility types have appeared in the literature.

The approach developed in the present chapter has a definition of the flexibility type, followed by an investigation into three dimensional factors, and a development of measurement models with the flexibility attributes. This Chapter in this thesis proposes the measurement of process flexibility and routing flexibility describes the application of these two types of flexibility.

6.2 Routing flexibility

6.2.1 Definition

Researchers seem to be more interested in routing flexibility, as several reports associated with routing flexibility have been published and a number of definitions and concrete measurement models have been proposed in the literature. These will be reviewed in the following sections.

Before proposing an operational definition for the measurement, it is necessary to define the domain of the research subject of routing flexibility. The main objective of routing flexibility is focused on the consideration of a part. There are a set of routes which are all capable of producing the given part, if the system is designed to incorporate flexibility. However, when outlining the measurement model for the routing flexibility of a system, the whole set of part/product types should be included.

Routing flexibility is generally defined as the ability of a production system to produce a set of producible part/product types smoothly without experiencing a fatal degeneration of production efficiency when internal (e.g., machine breakdown) and/or external (e.g., rush orders) disturbances occur. Such an achievement mainly relies on the system's alternative routes. This definition is similar to Bernado and Mohamed (1992). It has been common agreement that the more alternative options for a part/product, the more flexible the system appears. By following Sethi and Sethi's (1990) definition, Chen et al. (1992) also defined the routing flexibility of a manufacturing system as the ability to process a given set of part types using more than one route through the system.

Many definitions have appeared in the research reports consistent with such an idea. For example, Gerwin (1982) defined routing flexibility as the ability of the system to reroute a given part if the machine used in its manufacturing is incapacitated. The definition of Azzone and Bertele (1987) is consistent with Gerwin's (1982). The ability to vary machine visitation sequences and to continue producing the given set of part types is the definition given by Browne et al. (1984) and Hyun and Ahn (1992).

Carter's (1986) definition seems more detailed in defining routing flexibility as "the ability of the system to perform operations on alternate machine, in alternate sequences, or with alternate resources". Actually, this definition shares characteristics with those stated above.

Frazelle's (1986) definition of the ability of the system to dynamically assign parts to machines quickly and economically is slightly different from the others. However, the definition embodies the efficiency concept. Time and cost factors have been suggested for considerstion. Barad and Sippler (1988) emphasized that routing flexibility should be product mix dependent, which retains the same classical definition as others (Gupta and Gyoal 1989).

6.2.2 Three dimensions of routing flexibility

6.2.2.1 Range dimension

The number of alternative routes for a part/product or a part/product mix has been regarded as a common factor by researchers when measuring routing flexibility. A number of researchers have agreed with such a viewpoint and proposed several related approaches for the measurement. For example, the average number of routes available for a product (part) was suggested by Chatterjee et al. (1984), Chung and Chen (1989), Sinha and Wei (1992), and Zahran et al. (1990); the ratio of the existing number to the possible number of links between machines in the given system, proposed by Carter (1986), and the ratio of actual paths to the ideal paths of the system, proposed by Primerose and Leonard (1986), were an extension of the range dimension consideration. Chung and Chen (1990) suggested the ratio of the number of feasible routes for a part, to the total number of parts as the measurement of routing flexibility. Chen and Chung (1996) further characterized it as potential routing flexibility. While the actual routing flexibility was expressed as the ratio of the actual number of routes used by a part type to the total number of part types.

Nagarur's (1992) contribution suggested that the proportion of all potential routes that are available for each part should also be included in the range dimension; however, this consideration involves the potential ability of the system not just the demonstrated one. Bernado and Mohamed (1992) distinguished between actual routing flexibility, depicted by the number of existing production routes for a part, and potential routing flexibility, depicted by the total number of available routes to make a given part.

Routing entropy, depicted by the information contained in the list of operations and the machines, proposed by Yao (1985) and Yao and Pei (1990) should also be in the range application. The entropy approach applied to the measurement of routing flexibility was expressed as the function of the breakdown frequency of the machines in the system. The approach assures that an increase in the alternative routes for a part/product will increase the value of routing entropy. Range dimension, which is related to the versatility attribute defined by this thesis, is a partial consideration of the flexibility measurement.

6.2.2.2 Time dimension

The time dimension is also a significant factor in the consideration of routing flexibility measurement. There are a number of suggestions regarding time related applications to the measurement, e.g., percentage decrease in the throughput because of machine breakdowns (Buzacott, 1982), percentage reduction in total job completion time due to its presence when compared with the use of fixed routes (Chung and Chen, 1989), and decrease in throughput because of a machine breakdown (Gerwin, 1987). Throughput time applied to the measure was proposed by Falkner (1986).

6.2.2.3 Cost dimension

It appears that researchers have not yet paid a great deal of attention to applying the cost dimension to the measurement of routing flexibility. The only suggestion with respect to the cost consideration could be Browne et al.'s (1984) concerning the cost of production lost due to rescheduling or having to cope with a rush job for re-routing the production. However, they did not suggest concrete measurement method for the application. Obviously, there are a number of factors associated with cost which could be considered. At the least, setup cost, processing cost and transportation cost should all be considered in the measurement.

6.2.3 The measurement of routing flexibility

Sarker et al. (1994) suggested three factors for the measurement of routing flexibility, namely: (1) the number of routes available for the processing of a part; (2) the efficiency of each route; and (3) availability/utilization of routes.

The first factor could be considered the basic element of the concept, but should not be the only one for the measurement of routing flexibility. Such a consideration would be similar to the average number of alternative routes available for processing each part (Sinha and Wei, 1992), or the proportion of all potential routes that are available (Nagarur, 1992).

Chandra and Tombak (1992) proposed a mathematical model to evaluate the contribution of routing flexibility. They suggested that there is a need to take into account the reliability of machines and combined it for the measurement. They concluded that using more routes do not necessarily contribute more than using fewer routes.

However, this thesis argues that Chandra and Tombak's (1992) approach seems to rely too much on the reliability factor in the measurement model. If the two cases proposed in their report are examined in detail, it can be seen that the sum of total reliability of the machines in the three-machine case is less than in the two-machine case. In their model, it seems that reliability is the major factor affecting the contribution of a system, not its alternative routes. It could be concluded that if there is a 100% reliable machine, there is no need to have redundant machines. Therefore, there is no need to have routing flexibility. However, if the utilization of a machine has been taken into account and the machine is occupied by another job, a new job will have to wait in the queue.

Zahran et al. (1990) measured routing flexibility with more thorough considerations. They proposed that routing flexibility is a function of the number of available alternative routes, the efficiency of each route, and the availability of each route. However, although they considered the number of alternative paths for processing a part, the versatility did not appear in the model, due to taking the average of the total routes. The versatility consideration should reveal that the more alternative paths there are available for producing a part, the more flexible is the system.

The measurement of availability of each route, however, is a further consideration to the routing flexibility, since the condition has been changed. Normally, researchers regarded it as an off-line condition when measuring routing flexibility. Utilization of facilities is considered as an on-line situation. When the system is in doing work, the facility's utilization can readily be pointed out. Such a consideration seems to be more realistic. However, this thesis is not going to include such a consideration into the measurement model, because the consideration basis should be changed from the off-line to an on-line situation. This is not consistent with this thesis' basic assumption.

The consideration of the measurement of routing flexibility should take into account the following factors: (1) routing efficiency, (2) routing versatility, and (3) routing variety. Therefore, the measurement of routing flexibility should be a function of the following factors:

1. the number of alternative routes: The more alternative routes available, the more flexible is the system;
2. the efficiency of each route: The more efficient the path is on producing a part, the more flexible is the system;
3. the variety of the feasible routes set: The greater the difference between the routes, the more flexible is the system.

6.2.3.1 Routing efficiency

Gerwin (1987) suggested a measure of re-routing flexibility and proposed its measure as the drop in production rate when a machine breakdown occurred. This is consistent with the concept of efficiency rating. Azzone and Bertele (1989) proposed the same idea of the measure of the ratio between its expected production and the production of the fully operating system.

The efficiency measurement of a route should include the capabilities of the route in the forms of machines' reliabilities, processing times, processing costs, and the processing quality within each route. However, from a review of the measurement dimension in the literature, time seems to be a more attractive factor than any of the others, even cost, to the researchers in the measurement of routing flexibility, because time is likely to be a dominant factor for expressing the concept of routing flexibility.

The measurement of routing efficiency, proposed by Zahran et al. (1990), is based on the efficiency of machines. The efficiency of a machine in producing a part is a function of comparing the processing time and setup time to the minimum time for processing and setting up a machine for a part. Therefore, the efficiency of a route compares the summation of setup times and processing times of the route with the minimum summation of setup times and processing times within the set of available routes. However, Das (1996) evaluated a route's efficiency merely by comparing the shortest processing time of the route with its actual processing time.

This thesis suggests that throughput time of the part or flow time could be a more thorough measure of routing efficiency. The efficiency of a routing with time consideration, proposed in this thesis, could be the comparison of its actual flow time with the minimum flow time in the set of the routes. The flow time of a route should include the setup times, processing times, transportation times, loading/unloading times, waiting time and queuing times in the system of the part, as Frazelle (1986) stated that routing flexibility relies on material handling flexibility. Therefore, more time related factors should be added to the consideration than in that of process flexibility measurement.

A simplified approach could more plausibly be to make a clear perception to measure the efficiency of a route to produce a part. The approach could be a comparison of the flow time of the route with the minimum flow time in the set of routes. The flow time of a route is the summation of part loading/unloading times, machine setup times, processing times, and transportation times between the machines. Therefore, the efficiency of part j produced by route i, denoted as e_{ij}, is to compares the minimum flow time in the possible set of routes to the flow time of the evaluated route i. The function of a route efficiency in the set of routes is expressed as (6.1).

$$e_{ij} = \frac{Min_{i=1}^{r}[F_{ij}]}{F_{ij}} \tag{6.1}$$

where r = the number of possible processing routes for producing part j

i, j = subscripts for route and part, respectively

F_{ij} = the flow time of the route

The DEA approach is applicable to the measurement of routing efficiency. The first task is to define the input and output variables of a route. The input variables could include setup times, processing times, loading/unloading times, transportation times, setup cost, processing costs, loading/unloading costs, and transportation costs. While the output variables are the output quantity and the output quality of the route. A conceptual framework suggested by this thesis is expressed in Figure 6.1.

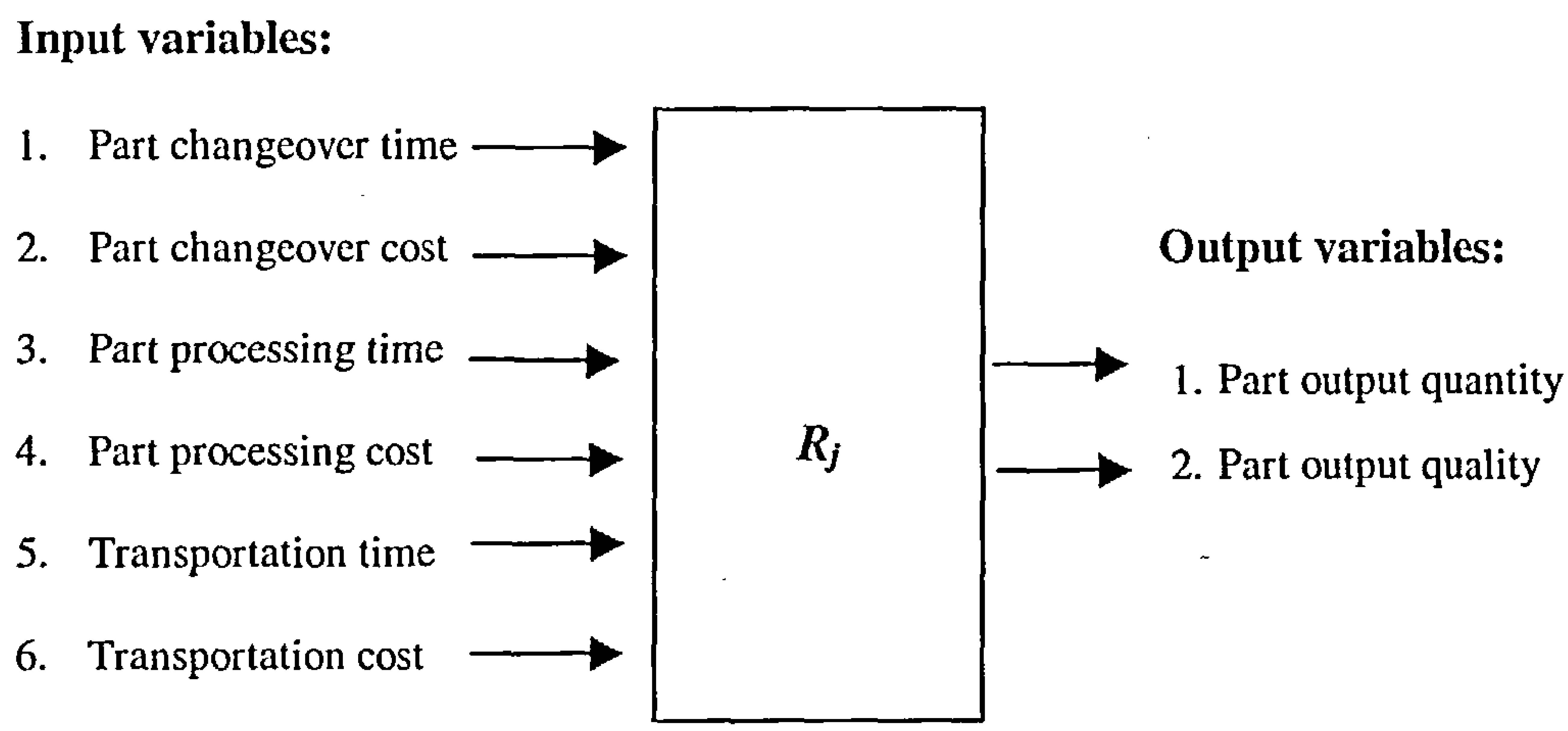


Figure 6.1: A conceptual framework of routing efficiency measurement

After making r calculations with the DEA model, r efficiency values will be obtained.

$$\Phi(e_{ij}^{r}) = (e_{1j}^{r}, e_{2j}^{r}, \cdots, e_{rj}^{r}) \qquad (6.2)$$

The routing efficiency on producing part type j can therefore be calculated as the average of the total efficiency values of the routes.

$$E_{j}^{r} = \frac{1}{r}\sum_{i=1}^{r} e_{ij}^{r} \qquad (6.3)$$

6.2.3.2 Routing versatility

The versatility of routing should illustrate that the greater the number of routes available for producing a part, the greater the flexibility of the system. The approach for measuring actual routing flexibility (ARF) and potential routing flexibility (PRF) proposed by Bernado and Mohamed (1992) are routing versatility considerations. The measurement of actual routing flexibility and potential routing flexibility for a given part j was expressed as:

$$ARF_j = 1 - (1/PR_j) \tag{6.4}$$

$$PRF_j = 1 - (1/AR_j) \tag{6.5}$$

where PR_j and AR_j represent actual production route assigned to the part j and total available routes in the system respectively. These measurement approaches are simple to use, but they do not include the whole features of routing flexibility. It would be too simplistic to count the number of possible processing routes for producing a part as the versatility.

The entropy approach would be another approach to satisfy the versatility requirement. When each route's efficiency on producing a part has been evaluated, then the part routing flexibility can be calculated. The routing versatility is expressed as (6.6).

$$\Re_j = -\sum_{i=1}^{r} \alpha_{ij} \log \alpha_{ij} \tag{6.6}$$

where α_{ij} represents the normalized efficiency value of part j produced by route i and r is the number of routes available for producing part j.

$$\alpha_{ij} = \frac{e_{ij}}{\sum_{i=1}^{r} e_{ij}} \tag{6.7}$$

6.2.3.3 Routing variety

The greater the number of routes that can be chosen, the more flexible the system is. Moreover, the quicker the throughput rate of one route, the more flexibility the system depicts. However, there are differences between the routes, and so the greater the difference among the routes, the more flexible is the system.

Routing variety measures the differences between the routes which are available for producing a part. It should show that the greater the differences between the routes, the more flexible the system should be. The difference between two routes, proposed by Das (1996) is evaluated on the basis of the machine visited and the corresponding processing times. When there are no common machines used between two routes, the difference is at its maximum 1.

However, this research argues that the difference between two routes can be simply calculated as the ratio of the number of different machines or machining centers visited to the total number of machines or machining centers in the two alternative routes. It will not be necessary to consider the processing time of the machines in the routes, as the processing time has been taken into account in the efficiency evaluation. The difference function could be expressed as (6.8).

$$d_{ij}^{r} = 1 - \frac{R_i \cap R_j}{R_i} \qquad (6.8)$$

where R_i and R_j denote any pair of routes of i and j, two sets of machining centers, which are both capable of producing the particular part/product. The numerator is denoted as the common machines within routes of i and j. While, the denominator is denoted as the set of visited machines within the routes i. Routes i and j will show no difference when the machines in two routes are all the same; while the difference will be at its maximum, i.e., the value of function (6.8) is 1, when there are no common machines visited between the two routes.

Flexible routing has been characterized as having alternative routes for producing a particular part/product. With respect to such a characterization, the consideration should focus on one part/product type which can be produced by different routes in the system. Therefore, there should be a set of feasible routes which are all capable of producing the evaluated part type. Suppose that there are r routes in the feasible routes set. There should be $r(r-1)$ pair comparisons. Therefore the total difference of the routes set is:

$$D^r = \frac{1}{r(r-1)} \sum_{j=1}^{r} \sum_{i=1}^{r} d_{ij}^r \tag{6.9}$$

6.2.4 Routing flexibility measurement

There are four factors which have been identified for the measurement of routing flexibility, including (1) routing efficiency, (2) routing versatility, and (3) routing variety. Suppose that there are k part types which have been evaluated in the system. Therefore, the routing flexibility of the system can be expressed as:

$$ROFLX_j = E_j^r \times v_j^r \times D_j^r \tag{6.10}$$

The total routing flexibility of produced part types is:

$$ROFLX = \frac{1}{k} \sum_{j=1}^{k} E_j^r \times v_j^r \times D_j^r \tag{6.11}$$

A brief summarization of the significant approaches, which are related to the measurement methods in routing flexibility, is given in Figure 6.2.

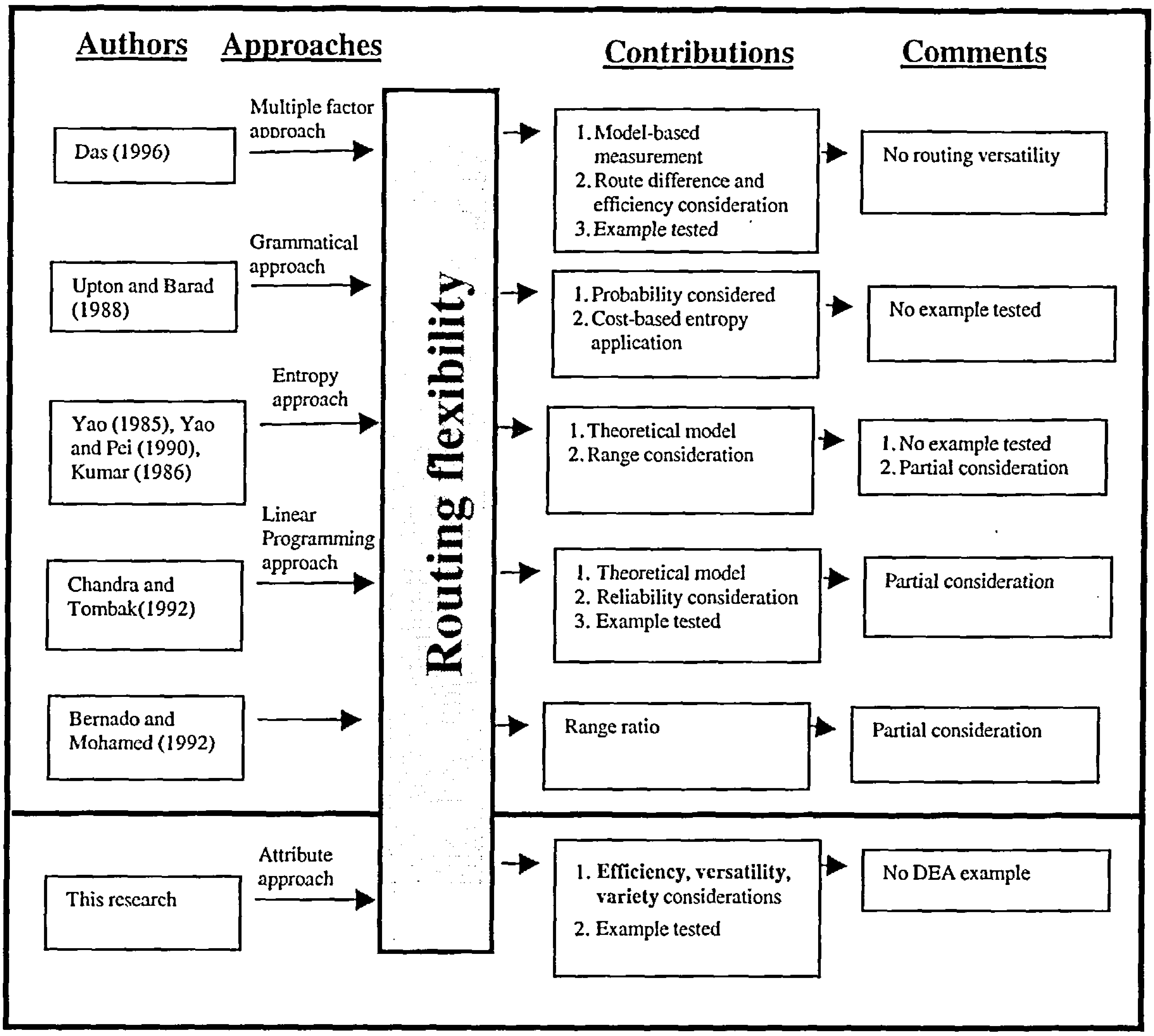


Figure 6.2: A brief review of routing flexibility

6.3 Process flexibility

6.3.1 Definitions

The advantage of a flexible production system is that the system is able to produce multiple products. Process flexibility is a measure of the ability of the system to manufacture a set of different types of part or product[1] without experiencing major setups. Therefore, process flexibility has been defined as the ability of a system to

[1] A manufacturing process is designed to produce a set of parts or products. For a more general explanation, part will be the chosen objective as the output instead of product in this Chapter.

produce a set of parts without a major effort to setup the production process (Carter, 1986; Azzone and Bertele, 1987; Sethi and Sethi, 1990; Chen et al., 1992; and Sinha and Wei, 1992). Most of the definitions are consistent with this viewpoint.

However, some other researchers seemed to possess different viewpoints. Process flexibility has also been defined as the ability to vary the steps necessary to complete a product (Browne et al., 1984). Frazelle's (1986) design change flexibility was defined as the ability of a system to implement engineering design changes for a particular part rapidly and inexpensively. Although the notation has been changed by Frazelle, however, it related to process flexibility. Chatterjee et al. (1984) addressed another viewpoint that a process flexible system is a system which is able to produce a product by different methods, in the forms of changing production sequence, using different tools, adapting to different raw materials, etc.

6.3.2 Three dimensions of process flexibility

In the literature it appears that researchers have seemed uninterested in developing concrete measures of process flexibility. This could be done to the deviations within the definitions. It would be helpful to obtain a clearer picture by investigating the measurement dimensions which have appeared in the literature. The three dimensions - namely range, time and cost - are illustrated as follows.

6.3.2.1 Range dimension

When process flexibility has been defined as the ability of a system to produce a set of part types with minor setup or effort, the measurement of process flexibility tends to focus on a measure of the number of part types that the system is able to produce within a major setup for the production. Browne et al.'s (1984) viewpoint was consistent with this; however, Browne et al. set the additional restriction that the part types could be processed simultaneously without batches. This is a simplistic method. Carter (1986) proposed that the measurement should consider the extent to which the product mix could be changed while maintaining efficient production. Therefore, process efficiency should be an additional factor to the measurement of process flexibility. To develop time and cost dimensions could lead to the understanding of process efficiency.

6.3.2.2 Time dimension

In the literature researchers have suggested some factors associated with the aspects of the time factor for the measurement of process flexibility. Those were average processing time per part (Jaikumar, 1986), average changeover time (Ettlie, 1988), average changeover time compare to average cycle time of machine (Carter, 1986), and setup times for producing a given product mix (Assone and Bertele, 1989).

6.3.2.3 Cost dimension

The cost dimension proposed in the literature is the changeover cost between different known jobs within the current production plan (Wernecke and Steinhilper, 1982), and the ratio of the total output and the waiting cost of parts processed for a given period (Son and Park, 1987). This thesis suggests that the cost dimension should be expanded to include processing costs.

6.3.3 The measurement of process flexibility

The measurement of a flexible process, proposed by the present research, should consider at least the following factors: (1) A wide range of part types being produced, (2) the process efficiency of each part type, and (3) the difference between part types.

6.3.3.1 Process efficiency

Process efficiency measures the ability of the equipped facility to produce the products without major setups or efforts in terms of time and/or cost. Son and Park's (1987) approach is an efficiency measurement consideration. Processing time, changeover time or setup time could also be applicable as the measurement of process efficiency.

To state things simply, the most efficient production process is one in which there is no waste of times and/or costs in the queue or on the waiting list for movement to the next servers. That means there are no non-value added times or costs incurred in the production process. The measurement criteria to capture this idea could be expressed by the ratio of value added processing time to the throughput time of a part produced by the process. Therefore, this thesis suggests that one way the efficiency of each part type k produced by the process, e_k^{ps}, could be obtained with the following function:

$$e_k^{ps} = \frac{\sum_{i=1}^{M} P_{ik}}{F_k} \tag{6.12}$$

and

$$F_k = \sum_{i=1}^{M} (S_{ik} + LU_{ik} + P_{ik}) \tag{6.13}$$

where

P_{ik} = processing times

F_k = flow time

S_{ik} = setup times

LU_{ik} = loading and unloading times

i, k = subscripts for machine and part type respectively.

However, it would be more plausible to state that an efficient production process could be described as one in which there is not only little time but also costs wasted in the queue. Moreover, there is no big difference of processing costs between the set of parts produced by the process. Theoretically, a production process should be designed to produce a particular type of part most efficiently. The idea of the value-add of processing times and processing costs of a part type produced by the process should be taken into account in the measurement. Then, the efficiency of each part type j produced by the process could be obtained with the DEA model.

Input and output variables need to be specified in the DEA model. Input variables include part changeover time, part changeover cost, part processing time, and part processing cost. The output variables are the output quantity and output quality of part type j, in which the former evaluates how quickly and the latter how well the system can produce outputs. A process is assumed to be concerned with the ability to manufacture. Therefore, there is no need to compare the transportation times and waiting times in the model.

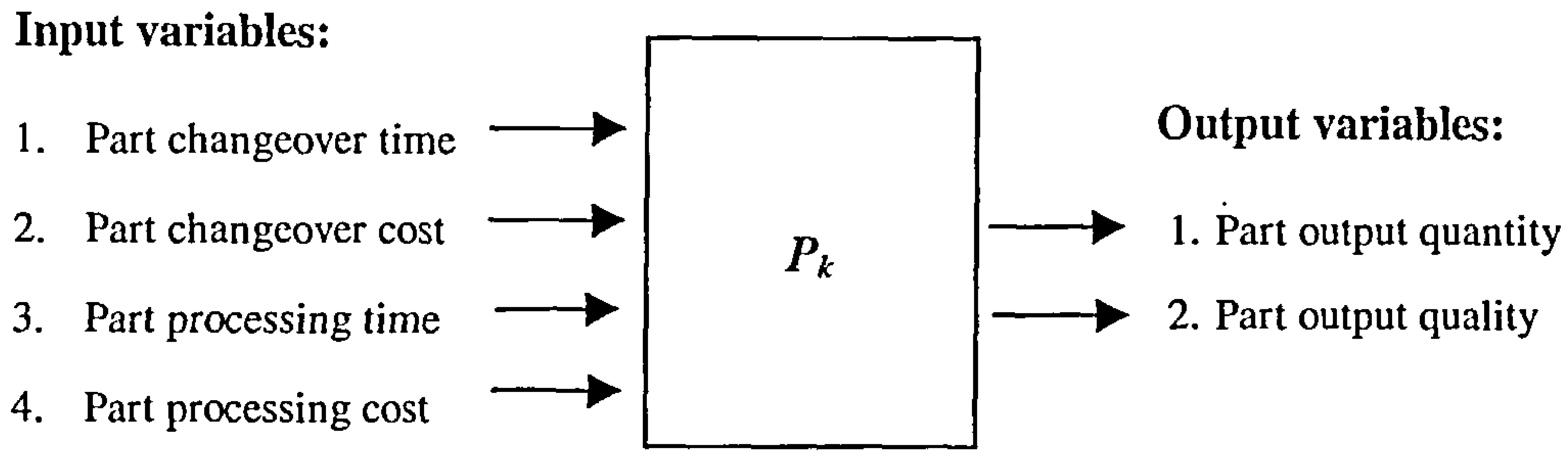


Figure 6.3: A conceptual model of process efficiency measurement

Finally, there is a set of efficiency values which represents the ability of a process to produce the set of part types.

$$\psi(e_k^{ps}) = (e_1^{ps}, e_2^{ps}, \ldots, e_n^{ps}) \tag{6.14}$$

Consequently, the process efficiency can be calculated as the average efficiency values of the set of part types produced by the process.

$$E^{ps} = \frac{1}{n}\sum_{k=1}^{n} e_k^{ps} \tag{6.15}$$

6.3.3.2 Process versatility

Process versatility is a measure of the possible range that the facility is equipped to produce. The more part types that can be produced by the process, the more flexibility it shows. Browne et al. (1984) and Jaikumar (1986) proposed a viewpoint consistent with this.

Following the evaluation of process efficiency of each part j by the DEA model, process versatility could be developed by the entropy approach as (6.5), in which it is possible to outline the constraint that the more part types produced by the process, the more flexible is the process.

$$v^{ps} = -\sum_{k=1}^{n} \varepsilon_k \log \varepsilon_k \tag{6.16}$$

where

$$\varepsilon_k = \frac{e_k^{ps}}{\sum_{k=1}^{n} e_k^{ps}} \tag{6.17}$$

and n represents the number of part types that the process is able to produce. ε_k is the normalized value of the produced part types and $\sum_{k=1}^{n} \varepsilon_k = 1$.

6.3.3.3 Process variety

Process variety measures the degree of difference between parts, which the facility is able to produce. It should show that the greater the difference between the produced parts, the more flexible the process. Das (1996) proposed that three factors could be considered, namely (1) processing operation difference, (2) operation precision requirement, and (3) the physical nature of the products. The first type of difference is measured as the percentage of tools not common to both products. The second type of difference captures the different skills required between two products. While, the physical nature reveals the difference of processing time at each machine.

"Variety measure" captures the difference between the output tasks. Alternatively, it could be the measurement of commonality between output tasks. However, the measurement of variety will show deviations at different system levels. At machine group level, for example, the output tasks are a set of operations, at a process level, it relates to a set of parts and at a plant level, it is associated with a set of products.

Briefly, a product consists of several parts, while a part consists of several operations. A process consists of several machines and operators, while a flexible machine or operator is able to perform several different operations to produce different kinds of products. Hence, different processes may produce an identical part/product. Moreover, a production process also comprises a set of operations, meaning a set of machines to visit. A part can be expressed as a set of operations and hence can be expressed as a set of process capable of producing the part. Therefore, when the differences between two products can be identified, it is probably sensible to develop the differences between the output states at the lower levels, and vice versa.

From the point of view of the process level, a part consists of a set of operations. The difference of part i to part j, d_{ij}^{c1} , is computed as the percentage of different operations to the total operations included in the part i.

$$d_{ij}^{c1} = 1 - \frac{O_i \cap O_j}{O_i} \tag{6.18}$$

where O_i and O_j represent the set of operations required for the parts i and j respectively. So, $0 \leq d_{ij}^{c1} \leq 1$. The numerator denotes the common operations required by the parts i and j; while the denominator denotes the total operations of part i. Parts i and j will have no difference when the operations for the two parts are entirely the same; while the difference will reach a maximum, and the value of the function (6.7) will be 1, when no common operation exits between the two parts.

The total difference between all parts will be:

$$d^{c1} = \frac{1}{n(n-1)} \sum_{j=1}^{n} \sum_{i=1}^{n} d_{ij}^{c1} \tag{6.19}$$

Secondly, it is necessary to consider the difference in the physical nature of the two parts, because this could affect loading and unloading. The factors of material, size, and shape of the part define these differences. Das (1996) suggested that Group Technology (GT) could be suitable for estimating this difference. The difference with respect to the viewpoint of physical nature of part types is denoted as d_{ij}^{c2}, and ranges from 0 to 1. d_{ij}^{c2} and d_{ji}^{c2} is defined as the same in this research. Therefore, the difference between two parts could be calculated as:

$$d^{c2} = \frac{2}{n(n-1)} \sum_{j=1}^{n} \sum_{i \succ j}^{n} d_{ij}^{c2} \tag{6.20}$$

When the difference between two types of part/product has been identified, it is necessary to consider the difference between the set of the output part/product types as a whole. The variety measurement approach developed in chapter 4 is applicable to the total difference between all pairs of part/product types that are produced by the process. Therefore, the process variety is measured by function (6.21).

$$D^{ps} = \theta_1 d^{c1} + \theta_2 d^{c2} \tag{6.21}$$

where θ_1 and θ_2 denote the weighted importance to the operation difference and physical difference respectively, and $\theta_1 + \theta_2 = 1$, therefore, $0 \le D^{ps} \le 1$.

6.3.4 Process flexibility measurement

Since process flexibility has been identified as the function of (1) process efficiency, (2) process versatility, and (3) process variety, it is proposed by this thesis as the equation (6.22).

$$PSFLX = E^{ps} \times v^{ps} \times D^{ps} \tag{6.22}$$

A brief review in process flexibility research is indicated in Figure 6.4.

6.4 Example illustration

The applications with the developed approach by this thesis should require in very detailed data form a factory, a job shop could the most typical example for the examination. It is worth to do empirical tests for the further researches. However, in order to keep the developed models tractable, this thesis used rather simple cases to test the models. This section presents the applications as example of the developed models in two facilities, which mainly extended from Das's (1996) report. Table 6.1 and 6.2 describe the parameters contained in the two facilities. Because of different approaches being generated by this thesis, some data have been transferred or applied in different ways. The DEA approach proposed by this thesis for the efficiency evaluation is not yet applied, because of the difficulties of obtaining the large amount of data. It should also need daily operations reports from the shop floor.

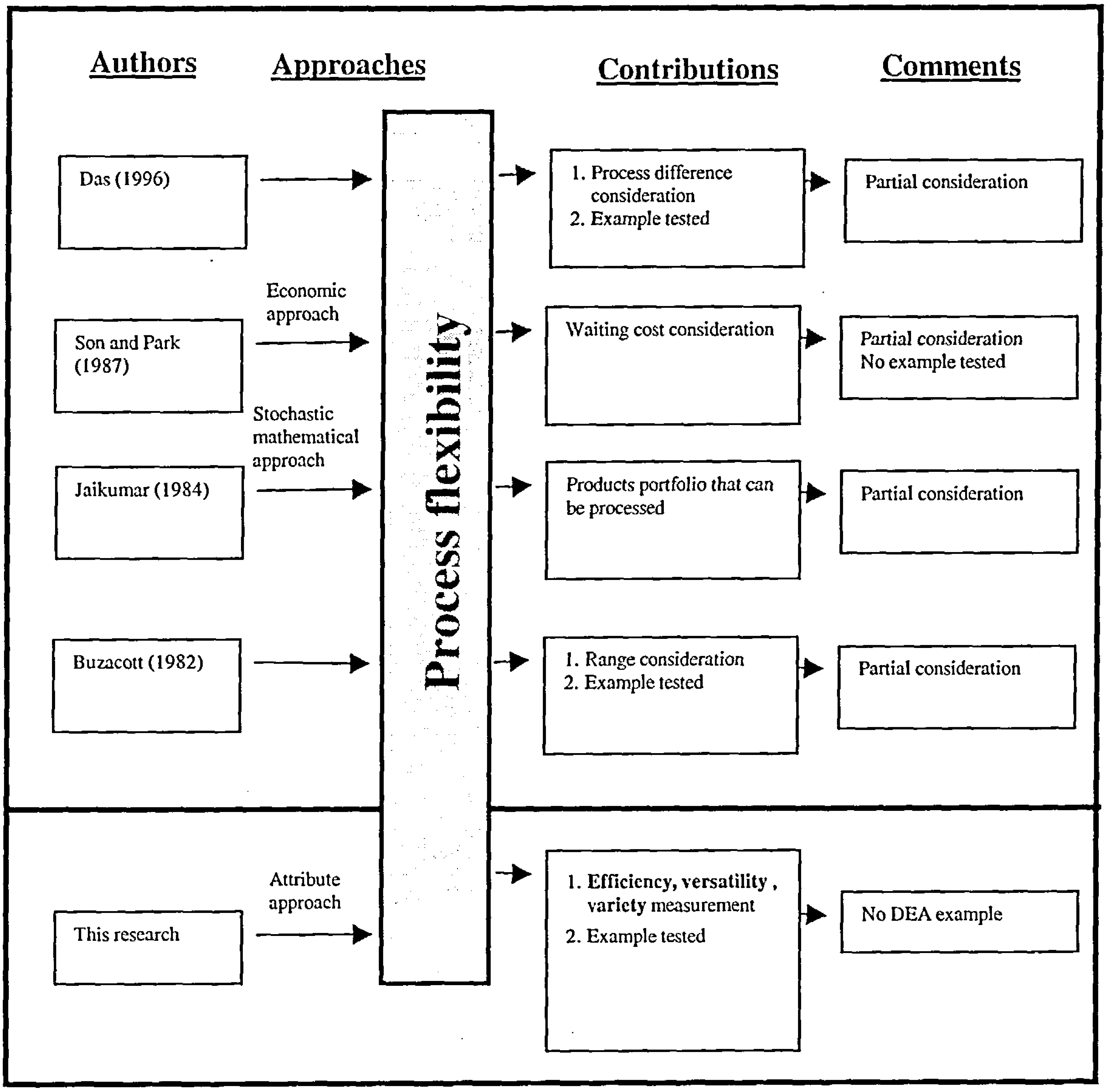


Figure 6.4: A brief review of process flexibility measurement

Table 6.1: Data for Manufacturing Facility # 1

(1) Number of operations (O_i) = 4, where $i = 1, 2, 3, 4$

(2) Number of machines (M_j) = 3, where $j = 1, 2, 3$

(3) Number of products (L_k) = 3, where $k = 1, 2, 3$

(4) Number of routes (R_r) = 2, where $r = 1, 2$

(5) Product manufacturing routes (P_{krj})

	Product k = 1			k = 2			k = 3		
Route #	j = 1	j = 2	j = 3	J = 1	j = 2	j = 3	j = 1	j = 2	j = 3
r = 1 Operations (I)	7 (1)	3 (2)	4 (4)	0 -	11 (4)	9 (2)	5 (1)	2 (2)	2 (4)
r = 2 Operations (I)	10 (1,3)	7 (2)	0 -	12 (1)	0 -	10 (4)	3 (1,3)	9 (2)	0 -

Product physical difference	k=2	k=3	
k=1	0.33	0.467	$d^{c2} = 0.443$
k=2	-	0.533	

Table 6.2: Data for Manufacturing Facility # 2

(1) Number of operations (O_i) = 5, where $i = 1, 2, 3, 4,5$

(2) Number of machines (M_j) = 4, where $j = 1, 2, 3,4$

(3) Number of products (L_k) = 3, where $k = 1, 2, 3$

(4) Number of routes (R_r) = 3, where $r = 1, 2,3$

(5) Product manufacturing routes (P_{krj})

	Product k = 1				k = 2				k = 3			
Route #	j = 1	j = 2	j = 3	j = 4	j = 1	j = 2	j = 3	j = 4	j = 1	j = 2	j = 3	j = 4
r = 1 Operations (i)	10 (2,3)	0 -	12 (1)	8 (2)	0 -	8 (2)	1 (3)	3 (5)	6 (2,3)	3 (4)	8 (2)	0 -
r = 2 Operations (i)	8 (5,3)	0 -	12 (1)	10 (2)	3 (3)	8 (4)	2 (2)	0 -	4 (5)	8 (3)	6 (4)	0 -
r = 3 Operation (i)	10 (5)	0 -	16 (1,3)	6 (2)	0 -	12 (3,4)	4 (2)	0 -	4 (1)	8 (4)	0 -	9 (5)

Product physical difference	k=2	k=3	
k=1	0.175	0.325	$d^{c2} = 0.317$
k=2	-	0.45	

6.4.1 Routing flexibility illustration of Manufacturing facility # 1 and # 2

Two routes from Table 6.1 and three routes from 6.2 for each product have been demonstrated in Table 6.3 and 6.4 respectively. The efficiency value of each route of one product is simply taken to be the ratio of the total processing time to the shortest route processing time. Once the efficiency values of all routes have been identified. The total route efficiency of a product can be calculated. Then, if each route efficiency value of a product have been brought into the entropy approach, the route versatility of the product is able to compute. The difference between two routes is available by considering the number of different machines visited. The difference value is to compute the ratio of common machines to the total machines in the two routes. Routing variety takes the average of the compared difference values.

The result of the **total routing flexibility of facility # 1** is 0.129; while **facility # 2** is 0.1965. In facility # 2, product 1 although has three routes to go through, actually, the three route are the same, because they visit the same machines. Therefore the routing flexibility of product 1 is zero. The total routing flexibility of facility # 2 should not include product 1 to the average computation. It shows that facility # 2 contains more flexibility than facility # 1, because each product in the former has more routes available for choice. However, the number of available routes is not the only factor to affect the routing flexibility value. Route efficiency and route variety also influence the system routing flexibility.

Table 6.3: Routing flexibility of manufacturing facility # 1

	Routes	Demonstrations	Total processing times $\sum_{i=1}^{4}\sum_{j=1}^{3} P_{1rij}$	Route efficiency (e_{kr})	Route variety
Product k=1	r = 1 (Processing time)	$a_{11} \rightarrow a_{23} \rightarrow a_{43}$ (7) (3) (4)	14	1.0	$\begin{array}{c} \\ R_1 \\ R_2 \end{array}\begin{array}{c} \begin{array}{cc} R_1 & R_2 \end{array} \\ \begin{bmatrix} 0 & 0.5 \\ 0.5 & 0 \end{bmatrix} \end{array}$
	r = 2 (Processing time)	$a_{11} \rightarrow a_{31} \rightarrow a_{22}$ (10) (7)	17	0.824	
	Computations	(1) $E^r_{k=1} = 0.912$ (2) $\Re_{k=1} = 0.299$ (3) $D^r_{k=1} = 0.5$ (4) $ROFLX_{j=1} = 0.136$			
Product k=2	r = 1 Processing time	$a_{42} \rightarrow a_{23}$ (11) (9)	20	1.0	$\begin{array}{c} \\ R_1 \\ R_2 \end{array}\begin{array}{c} \begin{array}{cc} R_1 & R_2 \end{array} \\ \begin{bmatrix} 0 & 0.5 \\ 0.5 & 0 \end{bmatrix} \end{array}$
	r = 2 Processing time	$a_{11} \rightarrow a_{43}$ (12) (10)	22	0.909	
	Computations	(1) $E^r_{k=2} = 0.955$ (2) $\Re_{k=2} = 0.3$ (3) $D^r_{k=2} = 0.5$ (4) $ROFLX_{j=2} = 0.143$			
Product k=3	r = 1 Processing time	$a_{11} \rightarrow a_{22} \rightarrow a_{43}$ (5) (2) (2)	9	1.0	$\begin{array}{c} \\ R_1 \\ R_2 \end{array}\begin{array}{c} \begin{array}{cc} R_1 & R_2 \end{array} \\ \begin{bmatrix} 0 & 0.33 \\ 0.5 & 0 \end{bmatrix} \end{array}$
	r = 2 Processing time	$a_{11} \rightarrow a_{31} \rightarrow a_{22}$ (3) (9)	12	0.75	
	Computations	(1) $E^r_{k=3} = 0.875$, (2) $\Re_{k=3} = 0.297$, (3) $D^r_{k=3} = 0.42$, (4) $ROFLX_{j=3} = 0.109$			

[Routing flexibility of facility # 1 ($ROFLX$) = 0.129]

Table 6.4: Routing flexibility illustration of manufacturing facility # 2

	Routes	Demonstrations	Total processing times $\sum_{i=1}^{4}\sum_{j=1}^{3} P_{1rij}$	Route efficiency (e_{kr})	Route variety
Product k=1	r = 1 (Processing time)	$a_{21} \rightarrow a_{31} \rightarrow a_{13} \rightarrow a_{24}$ (10) (12) 8)	30	1.0	
	r = 2 (Processing time)	$a_{51} \rightarrow a_{31} \rightarrow a_{13} \rightarrow a_{24}$ (8) (12) (10)	30	1.0	$\begin{array}{c c} & \begin{array}{ccc} R_1 & R_2 & R_3 \end{array} \\ \begin{array}{c} R_1 \\ R_2 \\ R_3 \end{array} & \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{array}$
	r = 3 (Processing time)	$a_{51} \rightarrow a_{13} \rightarrow a_{33} \rightarrow a_{24}$ (10) (16) (6)	32	0.938	
	Computations	(1) $E^r_{k=1} = 0.979$, (2) $\Re_{k=1} = 0.477$, (3) $D^r_{k=1} = 0.0$, (4) $ROFLX_{j=1} = 0.0$			
Product k=2	r = 1 (Processing time)	$a_{22} \rightarrow a_{33} \rightarrow a_{54}$ (8) (1) (3)	12	1.0	
	r = 2 (Processing time)	$a_{31} \rightarrow a_{42} \rightarrow a_{23}$ (3) (8) (2)	13	0.923	$\begin{array}{c c} & \begin{array}{ccc} R_1 & R_2 & R_3 \end{array} \\ \begin{array}{c} R_1 \\ R_2 \\ R_3 \end{array} & \begin{bmatrix} 0 & 0.33 & 0.33 \\ 0.33 & 0 & 0.33 \\ 0.33 & 0 & 0 \end{bmatrix} \end{array}$
	r = 3 (Processing time)	$a_{32} \rightarrow a_{42} \rightarrow a_{23}$ (12) (4)	16	0.75	
	Computations	(1) $E^r_{k=2} = 0.891$, (2) $\Re_{k=2} = 0.475$, (3) $D^r_{k=2} = 0.278$, (4) $ROFLX_{j=2} = 0.14$			
Product k=3	r = 1 (Processing time)	$a_{21} \rightarrow a_{31} \rightarrow a_{42} \rightarrow a_{23}$ (6) (3) (8)	17	1.0	
	r = 2 (Processing time)	$a_{51} \rightarrow a_{32} \rightarrow a_{43}$ (4) (8) (6)	18	0.944	$\begin{array}{c c} & \begin{array}{ccc} R_1 & R_2 & R_3 \end{array} \\ \begin{array}{c} R_1 \\ R_2 \\ R_3 \end{array} & \begin{bmatrix} 0 & 0 & 0.67 \\ 0 & 0 & 0.67 \\ 0.5 & 0.5 & 0 \end{bmatrix} \end{array}$
	r = 3 (Processing time)	$a_{11} \rightarrow a_{41} \rightarrow a_{54}$ (4) (8) (6)	21	0.81	
	Computations	(1) $E^r_{k=3} = 0.918$, (2) $\Re_{k=3} = 0.475$, (3) $D^r_{k=3} = 0.39$, (4) $ROFLX_{j=3} = 0.253$			

[Routing flexibility of facility # 2 ($ROFLX$) = 0.1965]

6.4.2 Process flexibility illustration of manufacturing facility # 1 and # 2

The process flexibility is focused on the ability of a system to produce a number of types of part/product. It concerns process efficiency, process versatility and process variety.

Suppose that each product is produced by the most efficient route within the feasible routes set. Those data are available form Table 6.3 and 6.4. The process efficiency of each process is expressed by the ratio of total processing time to the shortest processing time within the produced products. While the difference between two products is evaluated from the different operations, which have been taken by the two products, and the physical difference between the two products, which have been given in Table 6.1 and 6.2. The results of Table 6.5 and 6.6 show that facilities # 2 contain more process flexibility than # 1.

At this stage the efficiency value is compared using its own facility. An extension of the study could be compared to other facilities, as efficiency is a relative concept. Its value depends on a set of basis with which it is compared. This viewpoint is consistent with the concept of benchmarking.

Table 6.5: Process flexibility illustration of manufacturing facility # 1

Product	Demonstrations	Total processing times $\sum_{i=1}^{4}\sum_{j=1}^{3} P_{1rij}$	Process efficiency (e_k^{ps})	Product operation difference
K = 1 (Processing time)	$a_{11} \rightarrow a_{23} \rightarrow a_{43}$ (7) (3) (4)	14	0.643	
k = 2 Processing time	$a_{42} \rightarrow a_{23}$ (11) (9)	20	0.45	$\begin{array}{cc} & \begin{array}{ccc} K_1 & K_2 & K_3 \end{array} \\ \begin{array}{c} K_1 \\ K_2 \\ K_3 \end{array} & \begin{bmatrix} 0 & 0.66 & 0.33 \\ 0.15 & 0 & 0 \\ 0.33 & 1 & 0 \end{bmatrix} \end{array}$
k = 3 Processing time	$a_{11} \rightarrow a_{22} \rightarrow a_{43}$ (5) (2) (2)	9	1.0	
Computations	(1) $E^{ps} = 0.698$, (2) $v^{ps} = 0.455$, (3) $d^{c1} = 0.637$, (4) $d^{c2} = 0.443$ (5) $D^{ps} = \theta_1 d^{c1} + \theta_2 d^{c2} = 0.5 * 0.443 + 0.5 * 0.637 = 0.54$ (6) $PSFLX = E^{ps} \times v^{ps} \times D^{ps} = 0.168$			

Table 6.6: Process flexibility illustration of manufacturing facility # 2

Product	Demonstrations	Total processing times $\sum_{i=1}^{4}\sum_{j=1}^{3} P_{1rij}$	Process efficiency (e_k^{ps})	Product operation difference
K = 1 (Processing time)	$a_{21} \rightarrow a_{31} \rightarrow a_{13} \rightarrow a_{24}$ (10) (12) (8)	30	0.4	
k = 2 Processing time	$a_{22} \rightarrow a_{33} \rightarrow a_{54}$ (8) (1) (3)	12	1.0	$\begin{array}{cc} & \begin{array}{ccc} K_1 & K_2 & K_3 \end{array} \\ \begin{array}{c} K_1 \\ K_2 \\ K_3 \end{array} & \begin{bmatrix} 0 & 1 & 0.5 \\ 1 & 0 & 1 \\ 0.5 & 1 & 0 \end{bmatrix} \end{array}$
k = 3 Processing time	$a_{21} \rightarrow a_{31} \rightarrow a_{42} \rightarrow a_{23}$ (6) (3) (8)	17	0.706	
Computations	(1) $E^{ps} = 0.702$, (2) $v^{ps} = 0.45$, (3) $d^{c1} = 0.833$, (4) $d^{c2} = 0.317$ (5) $D^{ps} = \theta_1 d^{c1} + \theta_2 d^{c2} = 0.5 * 0.833 + 0.5 * 0.317 = 0.575$ (6) $PSFLX = E^{ps} \times v^{ps} \times D^{ps} = 0.182$			

6.5 Concluding remarks

Two process-orientated flexibility types, namely process flexibility and routing flexibility have been examined in this Chapter. Flexibility attributes developed by the present research have been applied to the measurement models.

Routing flexibility measurement has been suggested by this thesis as having three attributes which need to be considered simultaneously, namely routing efficiency, routing versatility and routing variety. First, routing efficiency according to this thesis is best obtained by applying the DEA approach. The input and output variables for the DEA model have been specified in this thesis. Secondly, routing versatility has been quantified by the entropy approach. Finally, routing variety compares the difference between the alternative routes. As long as those three attributes are considered together, routing flexibility can be demonstrated.

The configuration of the "routing flexibility measurement model" ensures that it should increase with (1) the increase in routing efficiency values on performing feasible routes, (2) the increase in the number of alternative routes, (3) the increase in the uniformity of the routing efficiency values, and (4) the increase in the routing variety.

The domain of routing flexibility is wider than that of process flexibility, as the process is focused on the setups for the processing and the processing ability only. For the measurement of routing flexibility however it is necessary to add more considerations, e.g., transportation between machines and/or machining centers.

It has been proposed that process flexibility should consider process efficiency, process versatility and process variety. The DEA is the best approach to use by this research for the measurement of process efficiency, while the entropy approach can be applied to process versatility measurement. Process variety is measured by the difference between output part types. A combined measurement model ensures that process flexibility should increase with the increase in the process efficiency values, the increase in the number of part types produced by the system and the increase in the uniformity of process efficiency values. Moreover, the increase in process variety, meaning the difference between the produced products, should increase process flexibility.

6.6 References

Azzone, G. and Bertele, U. (1987), "Comparing Manufacturing Systems with Different Flexibility: A New Approach", *Proceeding of The Decision Sciences Institute*, Boston, pp. 609-693.

Barad, M. and Sipper, D. (1988), "Flexibility in manufacturing systems: Definition and Petri-Nets Modeling", *International Journal of Production Research*, Vol. 26, No. 2, pp.237-248.

Bernardo, J. J. and Z. Mohamed (1992), "The Measurement and Use of Operational flexibility in the Loading of Flexible Manufacturing Systems," *European Journal of Operational Research*, 60, 144-155.

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P. and Stecke, K. E. (1984), "Classification of Flexible Manufacturing Systems", *The FMS Magazine*, 2 (2), pp.114-117.

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the 1st International Conference on FMSs*, Brighton, UK, pp.13-22.

Carter, M. F. (1986), "Designing Flexibility into Automated Manufacturing Systems." in *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems (Ann Arbor, MI),* K.E. Stecke and R. Suri (Eds), Elsevier, Amsterdam, The Netherlands, pp.107-118.

Chandra, P. and M. M. Tombak (1992), "Models for the Evaluation of Routing and Machine Flexibility," *European Journal of Operations Research*, Vol. 60, pp. 156-165.

Chatterjee, A., Cohen, M. A., Maxwell, W. L. and Miller, L. W. (1984), "Manufacturing Flexibility: Models and Measurements", in *Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems: Operations Research Models and Applications,* Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.49-64.

Chen, I. J., Calantone, R. J. and Chung, C. H. (1992), "The Marketing-Manufacturing Interface and Manufacturing Flexibility. *OMEGA*, 20 (4), pp.114-117.

Chung, C. H. and Chen, I. J. (1989), "A Systematic Assessment of the Value of Flexibility from FMS", in *Proceedings of the Third ORSA/TIMS Special Interest Conference on FMS*, New York: Elsevier.

Chung, C. H. and Chen, I. J., (1990), "Measuring Flexibility of Flexible Manufacturing Systems for Competitive Edge", in *Selection and Evaluation of Advanced Manufacturing Technologies*, M. Liberatore (ed.) (Berlin: Springer-Verlag), pp.280-305.

Chen, I. J. and Chung, C. H. (1996), "An Examination of Flexibility Measurements and Performance of Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 34, no. 2, pp.379-394.

Das, S. K. (1996), "The Measurement of Flexibility in Manufacturing Systems", *The International Journal of Flexible Manufacturing Systems*, 8, pp.67-93.

Ettile, J. E. (1988), "Implementation Strategies for Discrete Parts Manufacturing Technologies: Final NSF Report", University of Michigan (Ann Arbor, MI: University of Michigan).

Falkner, C. H. (1986), "Flexibility in Manufacturing Plant", in *Proceedings of 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, pp. 95-106.

Frazelle, E. H., (1986), "Flexibility: A Strategic Response in Changing Times", *Industrial Engineering*, March, pp.17-20.

Gerwin, D. (1982), "Do's and Don'ts of Computerized Manufacturing", *Harvard Business Review*, Vol. 60, pp.107-116.

Gerwin, D. (1987), "An Agenda for Research on the Flexibility of Manufacturing Processes", *International Journal of Operations and Production Management*, Vol.7, No.1, pp.38-49.

Gupta, Y. P. and Goyal, S. (1989), "Flexibility of Manufacturing Systems: Concepts and Measurements", *European Journal of Operational Research*, 43, pp.119-135.

Hyun, J. H. and Ahn, B. H. (1992), "A Unifying Framework for Manufacturing Flexibility", *Manufacturing Review*, Vol. 5, No. 4, pp.251-260.

Jaikumar, R. (1986), "Postindustrial Manufacturing", *Harvard Business Review*, Vol. 64, pp.69-76.

Nagarur, N. (1992) "Some Performance Measures of Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 30, pp. 799-809.

Primrose, P. L. and Leonard, R. (1986), "Conditions under Which Flexible Manufacturing is Financially Viable", in *Proceedings of the 3rd International Conference on FMS*, FMS, KFS (Publications) Ltd.

Sarker, B. R., Krishnamurthy, S. and Kuthethur, S. G. (1994), " A Survey and Critical Review of Flexibility Measures in Manufacturing Systems", *Production Planning and Control*, Vol. 5, No. 6, pp. 512-523.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Sinha, D. and Wei, C. (1992), "Stochastic Analysis of Flexible Process Choices", *European Journal of Operations Research*, Vol. 60, pp. 183-199.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advanced Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Upton, D. M. and Barad, M. M. (1988), "A Grammatical Approach to Routing Flexibility in Large Manufacturing Systems", *Journal of Manufacturing Systems,* 7, pp. 209-221.

Wernecke, H. J. and Steinhilper, R. (1982), "Flexible Manufacturing Systems: EDP Supported Planning; Application Examples", in: R. Lindholm (ed.), *Proceedings of the first International Conference on Flexible Manufacturing Systems*, North Holland, Amsterdam, pp345-356.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows 2* (Special Issue on Flexible Manufacturing System), pp.143-149.

Yao, D. D. and Pei, F. F. (1990), "Flexible Parts routing in Manufacturing Systems", *IEE Transactions*, Vol. 22, pp. 48-55.

Zahran, I. M., Elmaghraby, A. and Shalaby, M. A. (1990), "Evaluation of Flexibility in Manufacturing Systems," *IEEE International Conference on System, Man and Cybernetics*, pp149-152.

Primrose, P. L. and Leonard, R. (1986), "Conditions under Which Flexible Manufacturing is Financially Viable", in *Proceedings of the 3rd International Conference on FMS*, FMS, KFS (Publications) Ltd.

Sarker, B. R., Krishnamurthy, S. and Kuthethur, S. G. (1994), " A Survey and Critical Review of Flexibility Measures in Manufacturing Systems", *Production Planning and Control*, Vol. 5, No. 6, pp. 512-523.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Sinha, D. and Wei, C. (1992), "Stochastic Analysis of Flexible Process Choices", *European Journal of Operations Research*, Vol. 60, pp. 183-199.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advanced Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Upton, D. M. and Barad, M. M. (1988), "A Grammatical Approach to Routing Flexibility in Large Manufacturing Systems", *Journal of Manufacturing Systems,* 7, pp. 209-221.

Wernecke, H. J. and Steinhilper, R. (1982), "Flexible Manufacturing Systems: EDP Supported Planning; Application Examples", in: R. Lindholm (ed.), *Proceedings of the first International Conference on Flexible Manufacturing Systems*, North Holland, Amsterdam, pp345-356.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows 2* (Special Issue on Flexible Manufacturing System), pp.143-149.

Yao, D. D. and Pei, F. F. (1990), "Flexible Parts routing in Manufacturing Systems", *IEE Transactions*, Vol. 22, pp. 48-55.

Zahran, I. M., Elmaghraby, A. and Shalaby, M. A. (1990), "Evaluation of Flexibility in Manufacturing Systems," *IEEE International Conference on System, Man and Cybernetics*, pp149-152.

Chapter 7

Output-Orientated Flexibility Measurement

7.1 Introduction

Product is at the very end of a production process. A general flexible manufacturing system is concerned with not only the ability to product a wide range of different product types, but also the ability to vary production volume and production scale.

Slack's (1988) report tended to be an output-orientated flexibility proposal, as four-types of output flexibility was suggested in the research. These are product flexibility, mix flexibility, volume flexibility and delivery flexibility. Slack is possibly the only one who mentions delivery flexibility as a significant variable. Most researchers, Browne et al. (1984), Carter (1986), Azzone and Bertele (1987), Sethi and Sethi (1990), Chen et al. (1992), and Hyun and Ahn (1992) were more concerned with expansion flexibility.

To produce a wide range of variant products and introduce new products to market have been defined by the present research as the **capability** of the system. While, **capacity** is defined as the ability of a system to change its production rate. **Production flexibility** and **product flexibility** exhibit the output capability of the system; while **volume flexibility** pertains to output capacity. **Expansion flexibility** seems to be broader in concept, as it related to the ability of the system to handle an increase in capacity or a change in the product range (Carter, 1986). In short, expansion flexibility concerns with the ability to increase output capacity and capability of the system. The aims could be achieved in two ways. One is by duplicating current production resources to increase production volume; while, the other is by establishing functionally different production system to produce different product types. Expansion flexibility is the ability to change the production scale by extra capital investment on facilities or the employment of more labour.

The ability to change product mix and production volume is of most concern to managers in the short to medium term. Although product flexibility and expansion flexibility are also important to meet customers' needs and to achieve competitive requirements. This research, however, will focus on the former two types of flexibility, product mix and production volume.

7.2 Production flexibility

Production flexibility is **the ability of the system to produce product mix**. The domain of production flexibility could therefore be defined as the ability to produce a set of different types of product mix which the system is able to produce with no additional capital investment to the system.

Originally, researchers in this flexibility type used different terminology; however, the concept was preserved. Mandelbaum's (1978) *state flexibility* was defined as the situation where a given system is able to operate well in many different circumstances. Although the term used by Mandelbaum (1978) is different to production flexibility, the concept is consistent, as product mix change is also a change of the circumstance. Zelenovic's (1982) *application flexibility*, which was defined as the value of "design adequacy", the probability that the given structure of a system will adapt itself to environmental conditions and to customer requirements, within the limits of the given design parameters.

Gerwin (1982) used the term of mix flexibility and defined it as the ability of the system to simultaneously process a mix of different parts that are loosely related to one another. Frazelle (1986) echoed Gerwin's (1982) viewpoint, but slightly changed the term with product mix flexibility. Slack (1983) also adopted the term of product mix flexibility and defined it as the ability of the system to manufacture a particular mix of products within the minimum planning period used by the system, however, argued that simultaneous processing was not a necessary condition. The definitions of Carter (1986), Azzone and Bertele (1987), and Sethi and Sethi (1990) were all consistent with this.

Son and park (1987), Chen et al. (1992), and Hyun and Ahn (1992) retained the description that production flexibility is defined as the adaptability of a manufacturing system to enable change in product mix. However, Son and Park (1987) used the term product flexibility, which has caused some confusion in definition, as researchers have normally referred it as the ability of introducing new products.

The definition proposed by Browne et al. (1984) that the ability to vary the part variety quickly and economically for any product incorporates the efficiency concept. **The measurement of production flexibility should not only consider a range of product mix, but also the efficiency of producing them.**

In all, with the definitions in the literature, production flexibility encompasses multiple dimensions in concept. Therefore, **the measurement of production flexibility should**

include the number of product mixes and the ease, in terms of quickness and low cost of producing them.

7.2.1 Three dimensions of production flexibility

7.2.1.1 Range dimension

The range, which is equivalent to the number of product mixes, has been generally recognized as the main factor of the measurement of production flexibility. Browne et al. (1984) therefore proposed **the universe of part types, which the system can produce** as a considered factor for production flexibility. Moreover, the number of products which the company can produce, proposed by Muramatsu et al. (1985) and Bateman et al. (1999), and the size of parts produced by the system, proposed by Assone and Bertele (1989), are consistent with Browne et al. (1984).

Chatterjee et al. (1984) adopted the same viewpoint, but, added the restriction of retaining the same capital equipment. Cox (1989) suggested lot size as a subset of production flexibility. If it possesses production flexibility, the system will exhibit the ability to perform quick changeovers for different types of product and hence reveal the ability to launch small batch productions. Carter (1986) extended the concept to the extent of which product mix can be changed while maintaining efficient production.

7.2.1.2 Time dimension

It has been generally accepted that the setup time of a system to produce different product mix is a suitable element with which to express product mix flexibility. Setup time for each product mix was proposed by Cox (1989). There were a number consistent suggestions, including time needed to setup a production line (Barad and Sipper, 1988), the time required to switch from one part mix to another (Buzacott, 1982; Browne et al., 1984), and the changeover time (Bateman et al, 1999). Production cycle time, also proposed by (Cox, 1989), was another viewpoint.

However, it is argued here that the ability to produce a wide range of product mix efficiently is not just the ability to setup the system, but also the ability to produce them. Therefore, **setup time is not the only factor to take into account but also production lead time to produce the product mix has to be included.** The production lead time is defined as the time from receiving the order to the time of finishing it. On the other hand, unit throughput time could be another available factor for the measurement.

7.2.1.3 Cost dimension

Cost has been also proposed as a factor for production flexibility measurement. For example there are cost to change from one product to another (Buzacott, 1982; and Browne et al., 1984); changeover cost from one product mix to another (Chryssolouris and Lee, 1992); and work-in-progress inventory cost (Cox, 1989).

In order to keep a consistent viewpoint, cost dimension could be expanded to consider more than **changeover cost** or setup cost for producing different product mix. **Unit production cost** is another applicable factor for the measurement.

7.3.2 The measurement of production flexibility

It has been examined that a manufacturing system which has production flexibility should contain the ability to produce a wide range of product mixes, the ability to produce them at a high efficiency in terms of quickness and low cost, and the ability to produce a set of physical significantly different product mixes. Therefore, **production efficiency**, **production versatility** and **production variety** have all appeared to be necessary attributes for production flexibility measurement. Here, the present research suggests that **production autonomy** could be an additional attribute to include in the measurement of production flexibility, depicting that the system is able to produce the available output products by it self.

Production efficiency measurement is mainly based on the consideration of time and cost dimensions. Production versatility is focused on the number of product mixes which can be produced by the manufacturing system. Production variety is measured by the differences between the produced product mix. While, production autonomy measures the percentage of processing that is performed by the system.

7.2.2.1 Production efficiency

The ability to produce a product with high efficiency is to complete it with low wastes on non-value-added operations, including setup, queuing, waiting and moving. The most efficient production system is one which can produce the desired output with pure value-added activities. An applicable approach to evaluate production efficiency of a product is to compute the ratio of processing time to the total flow time, including setup times, queuing times for processing, processing times, waiting times for moving, and moving times.

There are a number of ways of producing an output successfully by a manufacturing system. This can be achieved by establishing an advanced manufacturing system with highly technology-intensive equipment, traditional labour intensive production systems with rather traditional production facilities, or by launching modern production management theory, e.g., Just-In-Time (JIT) production. For the first choice, the company is required to put in a considerable capital investment in order to establish a high-tech production system. Time saving is one of the advantages of a high-tech production system. The second choice is the traditional way of running a business. The systems rely more on labour rather than machine. The advantage of such a system is cost saving at the expense of time. By introducing modern production theory, manufacturing systems can reduce production lead time and production costs simultaneously, as they are focusing on reducing non-value added activities, e.g., quick setup training, multi-disciplined worker training, Quality Control Circle (QCC) activity running, etc.

Summarize, **time and cost are both suitable factors to be used in the efficiency measurement of producing a product**. With the **DEA approach**, it is suggested here that both factors are considered simultaneously and that associated factors should also be included in evaluation model.

The input variables selected in the measurement model of production efficiency of a product l (PR_l) include setup time, production lead time, setup cost and production cost;

while, the output variables are production quantity and production quality. Figure 7.1 illustrates the measurement model.

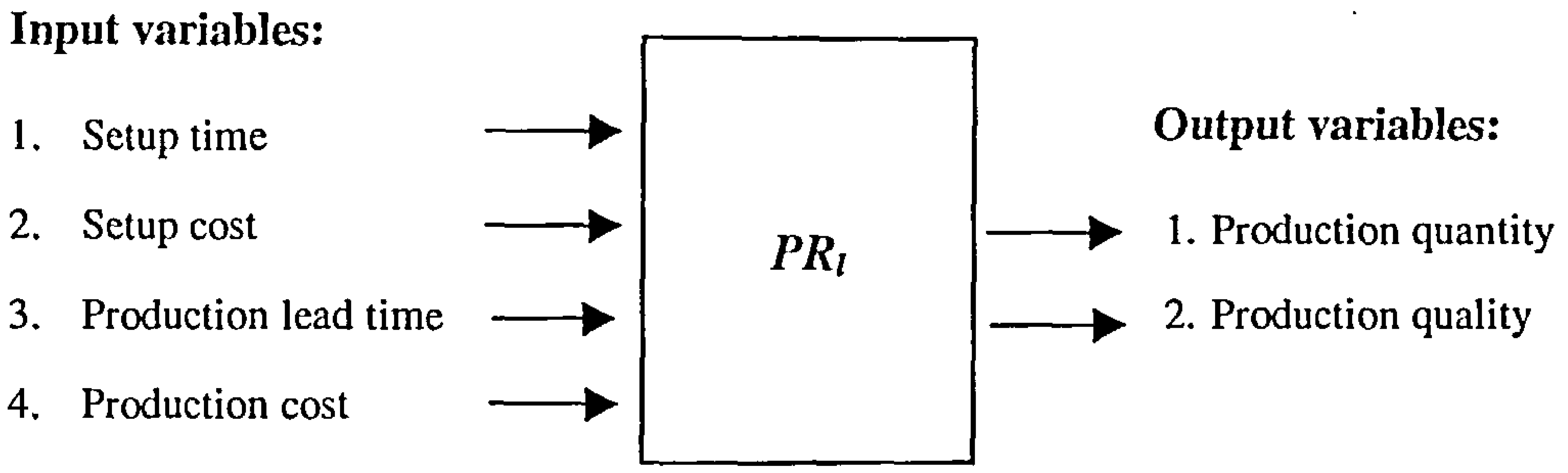


Figure 7.1: A conceptual model of production efficiency measurement

Suppose that there are m products have been evaluated by the DEA model, meaning that the system is able to produce m types of products. There will be a set of **production efficiency values** to be generated as follows.

$$\gamma(p) = (e_1^{pr}, e_2^{pr}, \cdots, e_m^{pr}) \tag{7.1}$$

where e_l^{pr} represents the efficiency value of the system on producing product l and $l=1,2,\ldots,m$.

The production efficiency of the manufacturing system can consequently be calculated as the average of the efficiency values of the product types produced by the system.

$$E^{pr} = \frac{1}{m}\sum_{l=1}^{m} e_l^{pr} \tag{7.2}$$

7.2.2.2 Production versatility

It has been the common recognition that the more product types are produced by a manufacturing system, the more flexible is the system. The **entropy approach** is also able to satisfy such a requirement. Since m production efficiency values have been identified as the ability of the system to produce m types of product, the production efficiency vector, given in equation (7.1), can be used in the entropy model. Therefore, the production versatility is:

$$v^{pr} = -\sum_{l=1}^{m} \mu_l \log \mu_l \tag{7.3}$$

where

$$\mu_l = \frac{e_l^{pr}}{\sum_{l=1}^{m} e_l^{pr}} \tag{7.4}$$

and m represents the number of product types that the system is able to produce. μ_l denotes the normalized value of the produced product types. Note that $\sum_{l=1}^{m} \mu_l = 1$.

7.2.2.3 Production variety

To consider the difference between the output products is another factor to consider in a production flexibility measurement. A method of measuring the differences between products proposed by Das (1996) should be the function of (1) the product handling procedure, (2) the operations, (3) the processing times, (4) the processing skills, and (5) the physical nature of products. These lead to the idea of this research which was to evaluate the differences at various system levels, because the product is at the very end of the production output and represents the highest level of the production structure.

However, it could be difficult, if the factors that mentioned above have all been applied to the measurement of the difference between two products, especially when the products are complicated, such as a vehicle. This research is therefore not intended to apply those five criteria into the measurement models. Rather, this research considers Gupta's (1993) suggestion that (1) the number of products in the product set produced by the system, (2) the degree of component commonality, and (3) the degree of processing commonality as the function for the measurement of difference. Since the first factor stated by Gupta (1993) and the processing times have been included in the versatility and efficiency measurement in the present research respectively, Here, in this thesis the variety measurement is taken to be the inverse of commonality with respect to the parts used between the products. Also, this research will take into account Das's (1996) viewpoint of the physical nature of the output tasks.

The approach of measuring the difference of a pair of products could follow the method developed in Chapter 6, process variety measurement. A product consists of several parts. Therefore, the difference of two products could count the different number of parts being used inside the two products. This could be expressed by (7.5).

$$d_{ij}^{P1} = 1 - \frac{P_i \cap P_j}{P_i} \tag{7.5}$$

where P_i and P_j represent the set of parts required for the product i and j respectively. And, d_{ij}^{P1} is ranged 0 to 1. The numerator denotes the common parts used by the two products, i and j. The denominator represents the total parts which has been used by product i.

It is also necessary to consider **the difference in physical nature between two products** as this might cause the difference when doing the assembly. The factors of material, size, and shape of the part could to used as a measure of difference. Group technology (GT) could also be used to measure such a difference (Das, 1996). The difference with respect to physical nature between two products is denoted as d_{ij}^{P2} and ranged as 0 to 1. Therefore, the difference between two products it is suggested here could be calculated as follows.

$$D_{ij}^{P} = \delta_1 d_{ij}^{P1} + \delta_2 d_{ij}^{P2} \tag{7.6}$$

where $\delta_1, \delta_2 \geq 0$, δ_1 and δ_2 are denoted as the weighted importance to the part difference and $\delta_1 + \delta_2 = 1$. D_{ij}^{P} denotes the difference between products i and j, and note that $0 \leq D_{ij}^{P} \leq 1$.

The total difference of the product set produced by the system is to take the mean value of the pair products differences. Therefore, production variety is calculated as (7.7)

$$D^{pr} = \frac{2}{m(m-1)} \sum_{j=1}^{m} \sum_{i \succ j}^{m} D_{ij}^{p} \tag{7.7}$$

where

m = the number of product types produced by the system

D_{ij}^{p} = the difference between a pair of product types, i and j.

7.2.2.4 Production autonomy

Strategically, a manufacturing system need not produce all products. Some components or subassemblies could be made by suppliers, as the suppliers may be more professional in making some components or subassemblies. These considerations concern the strategy of make-or-buy.

However, from a comparison point of view, a manufacturing system is thought to be more flexible, if it can produce the same set of products with a higher percentage of self-production. The consideration can be simply expressed as (7.8).

$$a_l^{pr} = \frac{SF_l}{TF_l} \tag{7.8}$$

where

a_l^{pr} = the self completion percentage of product l

SF_l = the span of flow time of product l within the system

TF_l = the total span of flow time to produce the product l

The **total completion percentage** is to take the mean value of the set of products produced by the system. Therefore, the production autonomy is denoted as follows.

$$A^{pr} = \frac{1}{m}\sum_{l=1}^{m} a_l^{pr} \tag{7.9}$$

7.2.3 Production flexibility measurement

The production flexibility has been developed as the function of (1) production efficiency, (2) production versatility, (3) production variety, and (4) production autonomy. Therefore, the model of production flexibility is expressed as (7.10).

$$FLX^{pr} = E^{pr} \times v^{pr} \times D^{pr} \times A^{pr} \tag{7.10}$$

The equation (7.10) has the following constraints:

(1) The function should increase with an increase of production efficiency.

(2) The function should increase with an increase of equally distributed efficiency values of the product types produced by the system.

(3) The function should increase with an increase of differences between the product types.

(4) The function should increase with an increase of production autonomy.

7.2.4 Discussion

Having the clear definitions of production versatility and product variety above, it is useful to examine the manufacturing flexibility as a competitive edge in manufacturing strategy. Production versatility is sustained by production variety. However, **production variety could not be always useful to the price-based competition**, as it may lead to an increase of production cost. The variation of products is not necessarily the number of completely different products. The products produced by the system could be different in appearance or the psychological sense to their consumers. Without appropriate change in manufacturing strategy, the increase of product variety leads to a drastic reduction in profitability (Leschke, 1995), as it increases manufacturing complexity and hence raises production costs. **This is one of the reasons why manufacturing flexibility is not always useful, unless it has been carefully investigated on flexibility attributes.**

It could also be unnecessary to increase production flexibility by relying upon production autonomy. Some parts and/or some assemblies could be cheaper to buy than to make, as professional producers may exist elsewhere. Strategic partnership is another option to consider when competing in the global marketplace.

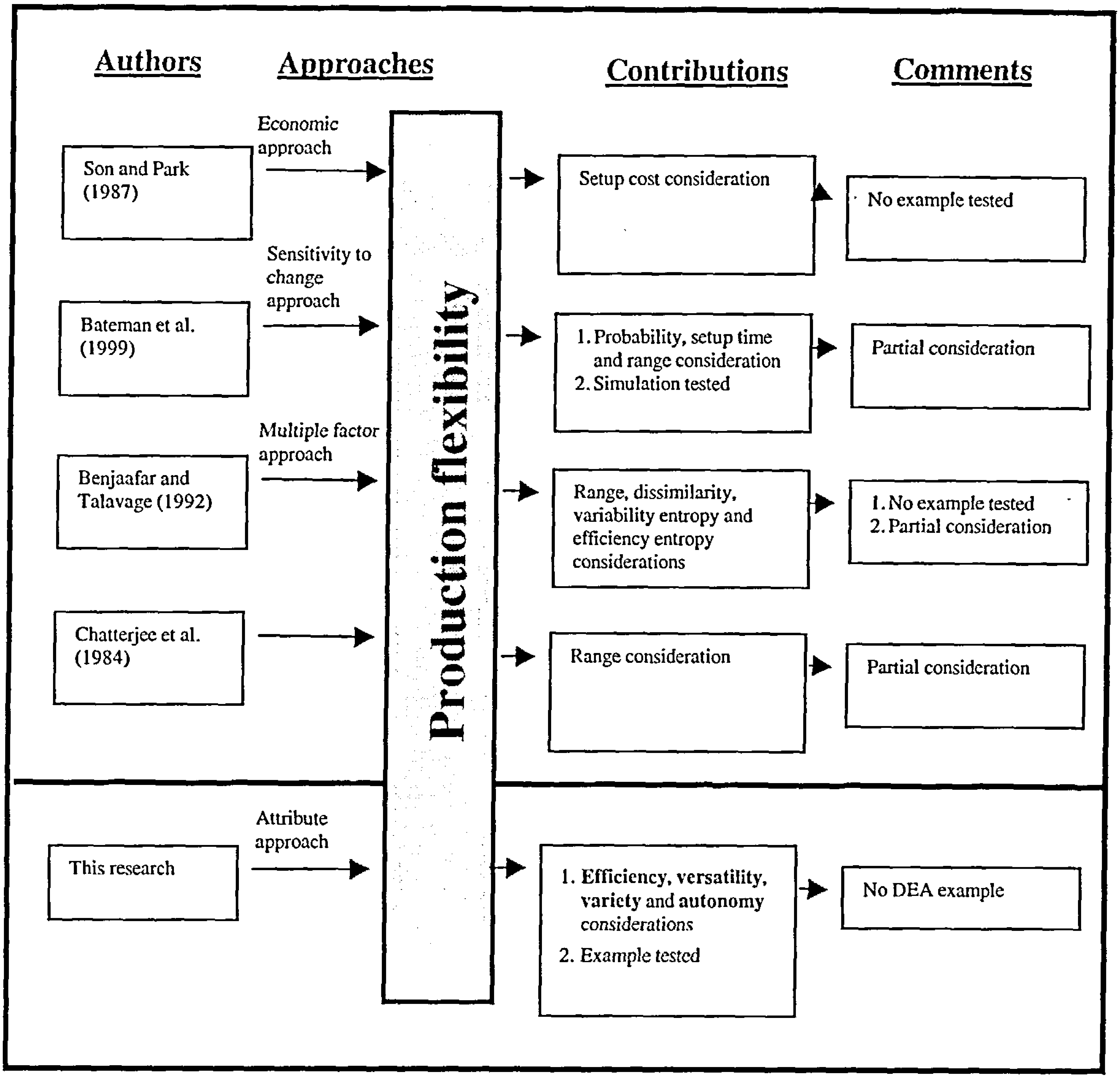


Figure 7.2: A brief review of production flexibility

7.3 Volume flexibility

Managers are generally concerned with demand changes, in terms of seasonal fluctuations or a decline in sale. In order to cope with such changes the managers need to rearrange facilities and adjust their manpower requirements. Especially, at the declining stage, some companies are struggling in making net profit to survive. Even further, the trend of a greater segmented market has forced companies to accept smaller volume of orders. This is in effect volume flexibility.

Das (1996) stated that one of the major concerns of managers is to meet customers' demands in the forms of volume changes and product type changes. The ability of a system to meet demand change could be reached by ways of accommodating the ability to change its production rate or by maintaining finished goods inventory. The latter could be the reason why Son and Park (1987) proposed inventory cost as the factor for the measurement of volume flexibility. A flexible system should not rely on high inventory to meet demand changes. However, the general view of researchers think that volume flexibility is reducing the gap between demand change rate and production rate.

Frazelle (1986) suggested that volume flexibility should require a flexible layout, which allows the system to change tools easily. The Toyota Production System reached such an ability with two approaches, in the forms of a U shaped layout and using multi-disciplined labour. The latter could well be the main way of coping with volume fluctuations. Production rate change is equivalent to the adjustment of throughput or cycle time. The achievement of such a requirement is to adjust the number of workers in the production process.

7.3.1 Definition

Volume flexibility is a popular research subject in manufacturing flexibility. Many definitions have been suggested and some concrete measurement models have appeared in the literature. There is little difference between researchers' viewpoint of definitions. Sethi and Sethi (1990) defined volume flexibility as the ability of a manufacturing system to be operated profitably at different overall output levels. Most definitions are consistent with Sethi and Sethi (1990), including Gerwin (1982), Slack (1983), Browne et al. (1984), and Chen et al. (1992).

The term "demand flexibility" labeled by Gustavsson (1984) and Son and Park (1987) is actually to configure the meaning of volume flexibility. The former was related to the possibility of demand fluctuation over a period, while the latter the adaptability to change in demand. Frazelle (1986) pointed out that the system with volume flexibility allows the accommodation of shifts in volume for a given part.

A more thorough definition of volume flexibility could encompass efficiency meaning. Azzone and Bertele (1987) defined it as the ability of a system to operate with a low reduction in the operating margin caused by a decrease in demand. Hyun and Ahn (1992) defined the volume flexibility as the ability to accelerate production very quickly and juggle the orders to meet demands for unusually rapid delivery, and to operate profitably at different production volumes. Barad and Sippler (1988) referred to as system setup flexibility. In all, the domain of analyzing volume flexibility is focused on a given product mix. The ability to vary production volume exists (Browne et al., 1984).

7.3.2 Three dimensions of volume flexibility

7.3.2.1 Range dimension

A measurement proposal of volume flexibility indicated by Browne et al. (1984) is the minimum volume of all part types that can be produced by the system profitably. The minimum volume was indicated at the point of the breakeven volume, where the revenue generated by the system is equal to the total production cost. However, in order to have a more general consideration, Sethi and Sethi (1990) suggested the measurement should include the range, from the lowest to the highest, of volumes that the system is capable of running. Gerwin (1987) used the ratio of average volume fluctuations to total capacity to measure volume flexibility.

Extending Browne et al. (1984) and Sethi and Sethi's (1990) viewpoint, Das (1996) proposed a utilization interval, which indicates running at the breakeven volume to the maximum capacity utilization in order to define volume flexibility. Das (1996) further pointed out that operating the facilities at or close to the breakeven volume is unlikely to be attractive to a company. The interval therefore was changed and indicated from the production volume with minimum hypothetical profit to the 100% utilization production volume. In short, these support the fact that the range is a factor for the measurement of volume flexibility.

7.3.2.2 Time dimension

Researchers seemed to be less interested in proposing volume flexibility measurement approaches with time factors. It is suggested in the present research that Sethi and Sethi (1990) could be the only one who suggested that volume flexibility could be measured by the time required to increase or decrease production volume by 20%.

However, this research argues that volume changes cause the managers to rearrange the facilities and reduce the number of workers. All these take time. When the volume change is bigger, time is necessarily longer. Therefore, setup time for the new production volume should be taken into account.

7.3.2.3 Cost dimension

Stigler (1939) could be the first one who measured volume flexibility using cost consideration. His idea was extended by Marschak and Nelson (1962), who suggested that volume flexibility could be expressed as the short-run average cost slope curves. Falkner (1986) suggested a measure of stability of manufacturing costs over widely varying levels of production volume. The ratio of the total output and the inventory/storage costs of finished products and raw materials for a given period was proposed by Son and Park (1987). Volume flexibility measurement is not only concerned with volume changes, but also with the costs caused by the changes of volume.

There should be at least two cost factors directly associated with volume flexibility measurement, namely volume setup cost and average production cost. As mentioned above, inventory is one way to cope with demand fluctuations. However, it is unlikely to show the way to efficient production. The most production system relies on its "just in time" production, with no waste in queue, in waiting list, in stock, and moving, not on inventory, in the forms of finished products, work-in-progress, or raw materials. Therefore volume flexibility measurement proposed by this thesis does not include inventory costs as a factor for the evaluation.

7.3.3 The measurement of volume flexibility

In practice, a company could set up a number of discrete production scales to cope with different volume of orders. When the production scale of a production order has been identified, the system could be easily setup. The feasible volume range should have the condition, which was indicated by Browne et al. (1984)[1] that volume flexibility is ranged from the volume at the breakeven point to the volume at the system's 100% utilization.

The research in this thesis defines a production scale as a state. There are a set of states, which represents that a set of production scales have been defined for the system to cope with different production volumes. Therefore, it is possible to evaluate the efficiency for each state. In all, there are two reasonable attributes to measure volume flexibility, namely volume efficiency and volume versatility,

7.3.3.1 Volume efficiency

Son and Park (1987) measured volume flexibility as the ratio of total output to the inventory costs. However, this thesis does not follow Son and Park's (1987) approach.

The efficiency at each state could take into account time and cost factors simultaneously. They are (1) the time to setup the system to produce a different volume, (2) the cost to do the setup, (3) the production cost of the volume, and (4) the production lead time of the volume.

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[1] In order to have a simplistic application at this stage, the feasible volume range adopts Browne et al.'s (1984) viewpoint, rather than Das's (1996).

The DEA approach can be used to measure volume efficiency. The input variables selected in the measurement model of volume efficiency of a given volume *r* (V_r) include setup time, production lead time, setup cost and production cost; while, the output variables are production quantity and production quality. Figure 7.3 illustrates the measurement model.

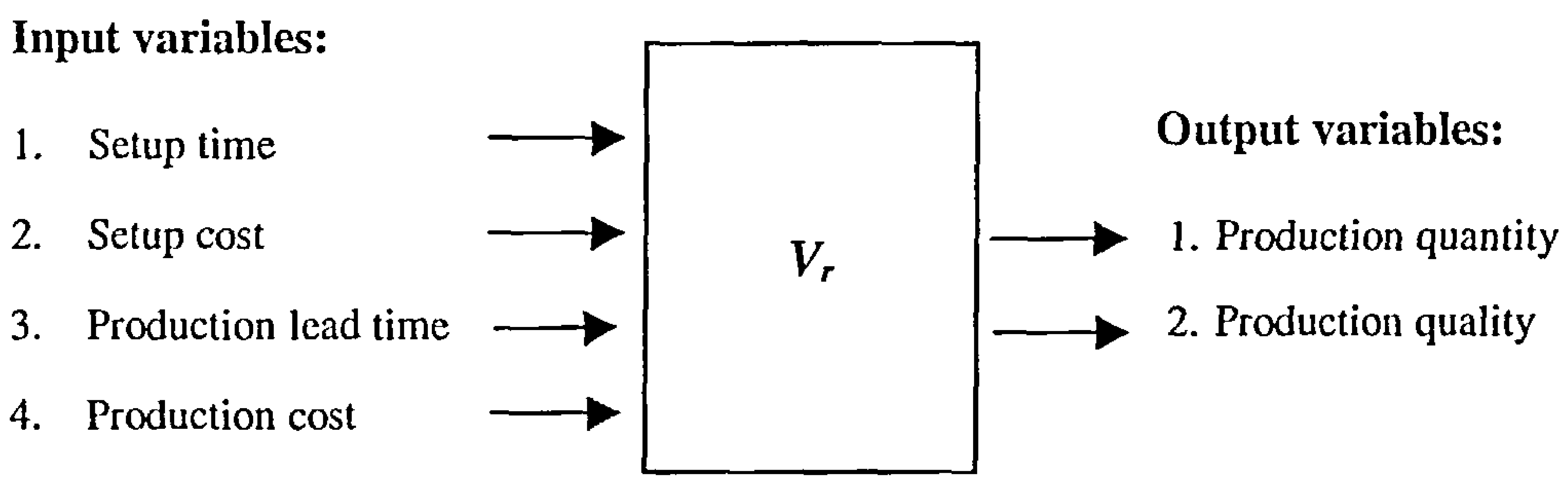

Figure 7.3: A conceptual model of volume efficiency measurement

Suppose that there are q states of production volume that have been evaluated by the DEA model, meaning that the system has been set up and ready to produce q different states of production volume. A volume efficiency vector can be generated as follows.

$$\lambda(v) = (e_1^v, e_2^v, \cdots, e_q^v) \tag{7.11}$$

where e_s^v represents the efficiency value of the system performing at scale s and $s = 1, 2, \ldots, q$.

The volume efficiency of the manufacturing system can consequently be calculated as the average of the efficiency values at over all states.

$$E^{v} = \frac{1}{q}\sum_{s=1}^{q} e_{s}^{v} \tag{7.12}$$

7.3.3.2 Volume versatility

It is also plausible to state that the more production volume states that have been set up by a manufacturing system, the more flexible is the system. The entropy approach is useful here. Since q volume efficiency values have been identified as the ability of the system to produce q scales of production, the volume efficiency values, illustrated in equation (7.11), can be brought into the entropy model. Therefore, the volume versatility is illustrated as (7.13).

$$v^{v} = -\sum_{s=1}^{q} \mu_{s} \log \mu_{s} \tag{7.13}$$

where

$$\mu_{s} = \frac{e_{s}^{v}}{\sum_{s=1}^{q} e_{s}^{v}} \tag{7.14}$$

and q represents the number of volume states that the system has been set up to produce. μ_{s} denotes the normalized value of the production scale and $\sum_{s=1}^{q} \mu_{s} = 1$.

There is another factor which should be taken into account. Two production systems with different feasible volume range could be setup with the same number of states of production scale. Therefore, in order to have a more thorough consideration, the feasible volume range should be brought into the model. Equation (7.15) depicts the feasible range, which is defined as **volume range.**

$$V^R = 1 - V_{BEP} \tag{7.15}$$

where

V^R = the feasible volume range that the system is able to produce profitably

V_{BEP} = the production volume at the breakeven point

7.3.4 Volume flexibility measurement

The volume flexibility has been developed as the function of (1) volume efficiency, (2) volume versatility, and (3) volume range. Therefore, the model of volume flexibility is calculated as (7.16).

$$FLX^v = E^v \times v^v \times V^R \tag{7.16}$$

Equation (7.16) has the following constraints:

(1) The function should increase with an increase of volume efficiency.

(2) The function should increase with an increase of equally distributed efficiency values of the volume sates established by the system.

(3) The function should increase with an increase of the feasible volume range.

A summarized volume flexibility measurement approach is given in Figure 7.4.

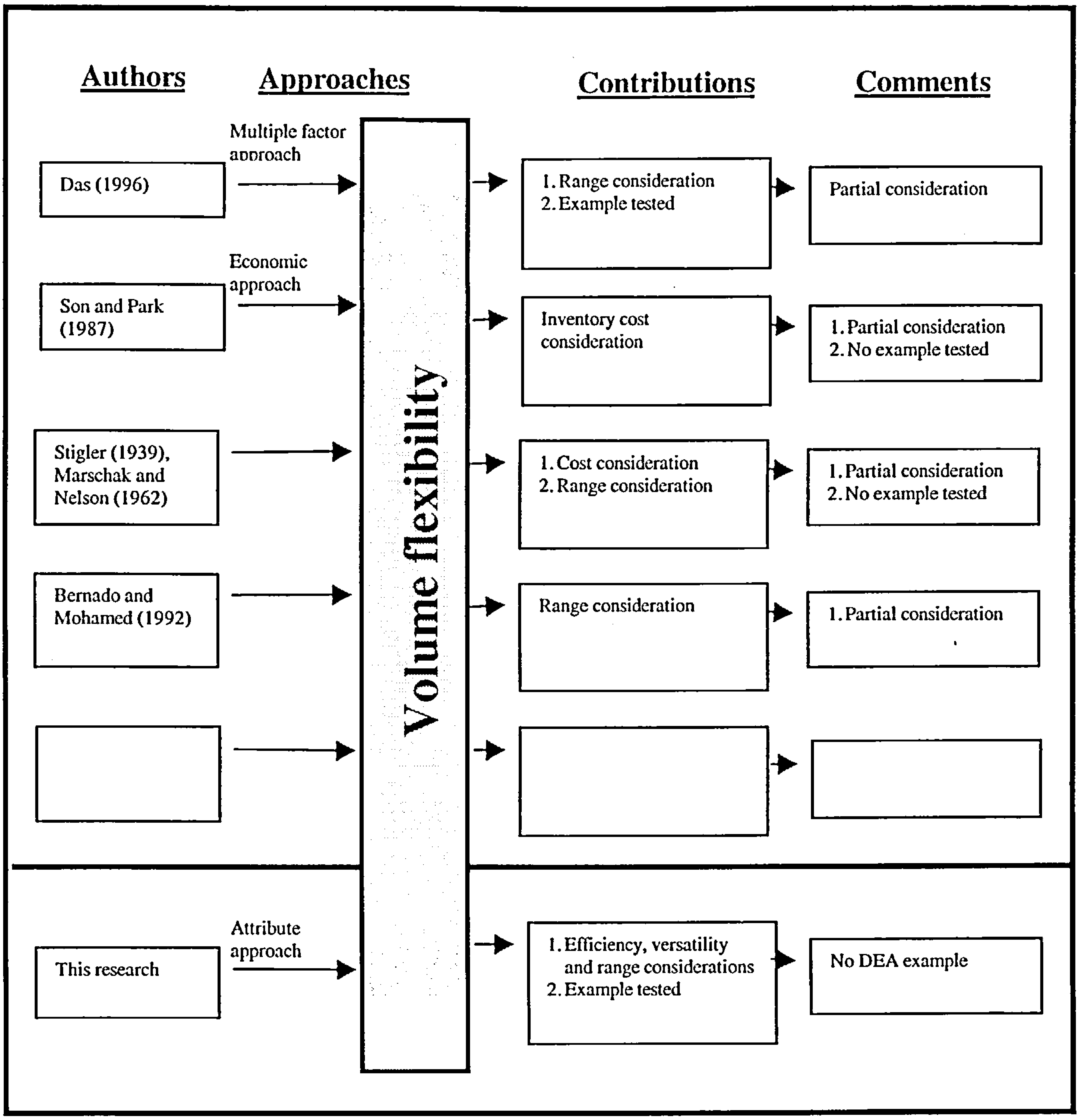

Figure 7.4: A brief review of volume flexibility measurement

7.4 Example illustration

7.4.1 Production flexibility measurement

Table 7.1 gives data of system A. There are 3 products and 5 parts produced by the system. The DEA approach is also not applied for efficiency evaluation here; instead the efficiency value of producing each product simply compute the ratio of production costs to the smallest product cost produced in the system. Product versatility is also evaluated by the entropy approach.

The production variety compares two factors, namely part difference and physical difference. The part difference compares the different part used between a pair of products; while the physical difference, proposed by Das (1996), could be available from Group Technology (GT). However, it could be an easier way to examine the physical difference between two products by counting the different number of parts and considering the different processing cost. For example, by looking into product 1 and 2 in Table 7.1, there are 2 rows and contain 10 cells. The physical difference between a pair of products takes the percentage of missing values in the 10 cells and half weight of the percentage of the cells, which contains the same part but with different production costs. The difference value of each pair of products is obtained in Table 7.2. The total part difference takes the average of the difference of the pairs of products; while total physical difference computes the average value of the total pairs of products physical differences. Finally, the product difference is simply weighted part difference and physical difference with 0.5 each.

The number with underline in the cells represents the part bought from its suppliers. The production autonomy is computed as the percentage of buying parts to the total parts used by the product. The production flexibility is computed by the average of total efficiency values, versatility, variety, and average product autonomy. The production flexibility value of system A is 0.072. The result seems significantly affected by the product difference. If the similarity is high between the products, it shows very low production flexibility.

Table 7.1: Data for system A

1. Number of products (L_k) = 3, where $k = 1, 2, 3$
2. Number of parts (N_l) = 5, where $l = 1, 2, 3, 4, 5$
3. Part production cost (C_{kl})

Product (k)	Part					Total costs $\sum_{l=1}^{5} C_{kl}$
	$l = 1$	$l = 2$	$l = 3$	$l = 4$	$l = 5$	
$k = 1$	(20)	(30)	(25)	<u>(40)</u>	-	115
$k = 2$	(25)	(25)	-	<u>(40)</u>	<u>(30)</u>	120
$k = 3$	(20)	(25)	(25)	(30)	(25)	125

Table 7.2: Product difference

	Product (k)	k = 2	k = 3		Weighted total difference
(1) Part difference	k = 1	1/4	1/10	0.15 (0.5)	0.2
	k = 2	-	1/10		
(2) Physical difference	Product (k)	k = 2	k = 3	0.25 (0.5)	
	k = 1	0.3	0.2		
	k = 2	-	0.25		

Table 7.3: Production attribute and their values

Product (k)	Product cost $\sum_{l=1}^{5} C_{kl}$	Production efficiency	Production versatility	Production variety	Production autonomy
k = 1	115	1.0	0.477	0.2	0.75
k = 2	120	0.958			0.5
k = 3	125	0.92			1.0

[$FLX^{pr} = E^{pr} \times v^{pr} \times D^{pr} \times A^{pr} = 0.069$]

7.4.2 Volume flexibility

Suppose that there are three systems to be evaluated, where 5 states have been set up for system A, 8 for system B and 4 for system C. Data are given in Table 7.4. Firstly, the efficiency value, with more thorough consideration, should evaluated by the DEA model. However, for a simply tractable consideration of the proposed model by this thesis, the efficiency of the system could directly concerned with the utilization of the system. At each utilization level, there is corresponding production efficiency. Secondly, the more production scales setup, the greater flexibility is the system. Thirdly, another factor affects the volume flexibility is the feasible range, which the system can profitably operate the system, where is ranged from breakeven point to the full utilization of the system.

Volume efficiency could be measured by the ratio of profit at the utilization level to the full utilization level. Volume versatility applies the entropy approach. It shows that the more states within the system, the greater volume flexibility. Volume range is computed by 1 minus the utilization.

Table 7.4: Data for system A, B, C

System A

States (*Ss*) = 5, where s = 1, 2, 3, 4, 5

Range (*Vv*) = 25%

State efficiency values (e_s^v):

	State					
	s = 0	s = 1	s = 2	s = 3	s = 4	s = 5
Utilization	75%	80%	85%	90%	95%	100%
Efficiency	0	0.5	0.7	0.85	0.9	1.0

System B

States (Ss) = 8, where s = 1, 2, 3, 4, 5, 6, 7, 8
Range (Vv) = 40%
State efficiency values

	State								
	s = 0	s = 1	s = 2	s = 3	s = 4	s = 5	s = 6	s = 7	s = 8
Utilization	60%	65%	70%	75%	80%	85%	90%	90%	100%
Efficiency	0	0.3	0.5	0.65	0.8	0.85	0.92	0.98	1.0

System C

States (Ss) = 4, where s = 1, 2, 3, 4
Range (Vv) = 40%
State efficiency values

	State				
	s = 0	s = 1	s = 2	s = 3	s = 4
Utilization	60%	70%	80%	90%	100%
Efficiency	0	0.5	0.8	0.9	1.0

The results of the three systems are given in Table 7.5. The volume flexibility of the system A, B and C are 0.136, 0.264 and 0.189 respectively. Table 7.5 demonstrates that the more states setup by the system, the greater volume versatility shows. And, consequently, it increases volume flexibility.

Table 7.5: Volume flexibility and its attributes

System	Volume efficiency	Volume versatility	Volume range	Volume flexibility
A	0.79	0.688	0.25	0.136
B	0.75	0.881	0.4	0.264
C	0.8	0.59	0.4	0.189

7.5 Concluding remarks

There have been four types of flexibility defined in the output-orientated flexibility, namely production flexibility, volume flexibility, product flexibility and expansion flexibility. However, this research at this stage has proposed the attribute approach only for the former two types of flexibility. The attribute approach is also equally applicable to the latter two. It is therefore worth for further research.

The attributes proposed in this research have been applied in this chapter including efficiency, versatility, variety and autonomy. The weights of importance have been proposed in the measurement of production variety.

The approaches, which have been chosen for the application in this chapter, is to keep a consistency with the approaches applied to the other types of flexibility and to confirm them sensibly reasonable and applicable to the measurement of the given flexibility type.

The approach, which has been applied to the production efficiency and volume efficiency measurement, also chooses the DEA model, as the factors are concerned with multivariate and it could be difficult to adopt a *priori* mathematical function to express the relationship between the variables. Versatility measurement also uses the entropy approach. However, in order to have a more thorough consideration of volume versatility, it is suggested here that the feasible volume interval should be included in the volume versatility model.

7.6 References

Azzone, G. and Bertele, U. (1987), "Comparing Manufacturing Systems with Different Flexibility: A New Approach", *Proceeding of The Decision Sciences Institute*, Boston, pp. 609-693.

Azzone, G. and Bertele, U. (1989), "Measuring the Economic Effectiveness of Flexible Automation: A New Approach," *International Journal of Production Research*, Vol. 27, No. 5, pp. 735-746.

Barad, M. and Sipper, D. (1988), "Flexibility in Manufacturing Systems: Definition and Petri-Nets Modeling", *International Journal of Production Research*, Vol. 26, No. 2, pp.237-248.

Bateman, N., Stockton, D. J., and Lawrence, P. (1999), "Measuring the Mix Flexibility of Manufacturing Systems", *International Journal of Production Research*, Vol. 37, No. 4, pp. 871-880.

Benjaafar, S. and Talavage, J. J. (1992), "Axiomatic Measure of Flexibility in Advanced Manufacturing Systems, 1992 *IEEE International Conference on Systems, Man and Cybernetics*, Vol. 2, #92CH3176-5.

Bernardo, J. J. and Mohamed, Z. (1992), "The Measurement and Use of Operational flexibility in the Loading of Flexible Manufacturing Systems," *European Journal of Operational Research*, 60, 144-155.

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P., and Stecke, K. E. (1984), "Classification of Flexible Manufacturing Systems", *The FMS Magazine*, 2 (2), pp.114-117.

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the 1st International Conference on FMSs*, Brighton, UK, pp.13-22.

Carter, M. F. (1986), "Designing Flexibility into Automated Manufacturing System." in *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems (Ann Arbor, MI)*, K.E. Stecke and R. Suri (Eds), Elsevier, Amsterdam, The Netherlands, pp.107-118.

Chatterjee, A., Cohen, M. A., Maxwell, W. L. and Miller, L. W. (1984), "Manufacturing Flexibility: Models and Measurements", in *Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, pp.49-64.

Chen, I. J., Calantone, R. J. and Chung, C. H. (1992), "The Marketing-Manufacturing Interface and Manufacturing Flexibility", *OMEGA*, 20 (4), pp.114-117.

Chryssolouris, G. and Lee, M. (1992), "An Assessment of Flexibility in Manufacturing Systems", *Manufacturing Review*, Vol. 5, No. 2, pp105-116.

Cox, J. T. (1989), "Toward the Measurement of Manufacturing Flexibility", *Production and Inventory Management Journal*, First Quarter, pp.68-72.

Das, S. K. (1996), "The Measurement of Flexibility in Manufacturing Systems", *The International Journal of Flexible Manufacturing Systems*, 8, pp.67-93.

Falkner, C. H. (1986), "Flexibility in Manufacturing Plant", in *Proceedings of 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, pp. 95-106.

Frazelle, E. H. (1986), "Flexibility: A strategic Response in Changing Times", *Industrial Engineering*, March, pp.17-20.

Gerwin, D. (1982), "Do's and Don'ts of Computerized Manufacturing", *Harvard Business Review*, Vol. 60, pp.107-116.

Gerwin, D. (1987), "An Agenda for Research on the Flexibility of Manufacturing Processes", *International Journal of Operations and Production Management*, Vol.7, No.1, pp.38-49.

Gustavsson, S. O. (1984), "Flexibility and Productivity in Complex Production Processes", *International Journal of Production Research*, Vol. 22, No. 5, pp.801-808.

Hyun, J.H. and Ahn, B.H. (1992), "A Unifying Framework for Manufacturing Flexibility", *Manufacturing Review*, Vol. 5, No. 4, pp.251-260.

Leschke, J. P. (1995), "Plastech - The Importance of Matching Production Capabilities and Market Requirements, *Production Inventory Management Journal*, Third Quarter.

Mandelbaum, M. (1978), *Flexibility in Decision Making: An exploration and Unification*, PhD thesis, Department of Industrial Engineering, University of Toronto, Canada.

Marschak, T. and Nelson, R. (1962), "Flexibility, Uncertainty and Economic Theory", *Metroeconomica*, Vol. 14, pp. 42-58.

Muramatsu, R., K. Ishii, and K. Takahashi (1985), "Some Ways to Increase Flexibility in Manufacturing Systems", *International Journal of Production Research*, Vol. 23, No.4, pp.691-703.

Sethi, A. K. and Sethi, S. R. (1990), "Flexibility in Manufacturing: A Survey", *The International Journal of Flexible Manufacturing Systems*, 2, pp.289-328.

Slack, N. (1983), "Flexibility as a Manufacturing Objective", *International Journal of Production Management*, Vol. 3, No. 3, pp.4-13.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advanced Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Stigler, G. (1939), "Production and Distribution in the Short Run", *Journal of Political Economy*, Vol. 47, June, pp. 305-327.

Chapter 8

Concluding remarks

8.1 Introduction

In the literature it can be seen that considerable contributions to the work in this area have been done by researchers. They have proposed definitions, suggested the measurement considerations and provided measurement approaches to clarify the concept of manufacturing flexibility. However, for the most part it has been incomplete and confused. This research has attempted to remedy this situation as well as to push the concept of flexibility forward in an integrated way.

A framework for clarifying manufacturing flexibility has been proposed in Chapter 1. The framework contains the relationship between manufacturing flexibility and its surroundings, including "manufacturing flexibility classification", "manufacturing strategy", "manufacturing environment", and "manufacturing objectives". A classified framework of Input-Process-Output (IPO) of manufacturing flexibility types has been proposed in the research presented in this thesis. It provides a better way to understand manufacturing flexibility.

Many studies have argued that there is no single measurement approach applicable to all types of flexibility of the manufacturing system at the operational level. For instance, the entropy approach has only been applied to operation flexibility, loading flexibility and routing flexibility (Kumar, 1986, 1987; Yao, 1985; Yao and Pei, 1990; Upton and Barad, 1990)); the economic approach has been applied to four types of flexibility, namely equipment flexibility, product flexibility, process flexibility and demand flexibility, by Son and Park (1987); Petri-Net approach was applied to machine flexibility (Barad and Sipper, 1988, 1990). Weighted effectiveness to the output tasks of machine flexibility and machine group flexibility measurement are given by Brill and Mandelbaum (1989). A dimensional approach, proposed by Slack, (1983), Gerwin (1987, 1993), goes only part way to the measurement of flexibility, as the dimensional factors namely range, time and cost are basic elements, but they do not cover all factors for flexibility measurement.

The reason why there is no unified measurement model to evaluate all types of flexibility is because of confused characteristics embodied in the flexibility concept. These have not yet been clearly identified, understood and integrated. One objective of this thesis is to identify, clarify and integrate all aspects of flexibility with a view to make possible a unified approach. It is possible based on this thesis, to state that there is now a real possibility of defining and using a unified measurement approach for the evaluation of all types of manufacturing flexibility.

This thesis suggests that as long as flexibility can be regarded as a system, the attribute approach could be applied to the measurement of manufacturing flexibility.

Three flexibility dimensions – range, time and cost – have been combined in this thesis and the flexibility measurement approach has been extended into ten types of flexibility attribute, namely efficiency, versatility, redundancy, variety, mobility, autonomy, control, learning, weighted importance and probability occurrence of the tasks. The structure of the manufacturing flexibility attribute proposed by the present research is illustrated in Figure 8.1.

Figure 8.1: A conceptual framework of manufacturing flexibility attribute

Table 8.1 summarizes the relationship between flexibility types, which have been examined by the present research, and flexibility attributes, which are proposed by the present research, marked with [✔]. In Table 8.1, it also indicates some possible applications, marked with [▲], and unsuitable applications, marked with [✖].

Table 8.1: The relationship between flexibility types and flexibility attributes

Flexibility types	Input-orientated flexibility		Process-orientated flexibility		Output-orientated flexibility	
Flexibility attribute	Machine flexibility	Machine group flexibility	Routing flexibility	Process flexibility	Production flexibility	Volume flexibility
Efficiency	✔	✔	✔	✔	✔	✔
Versatility	✔	✔	✔	✔	✔	✔
Variety	▲	▲	✔	✔	✔	▲
Redundancy	✖	✔	✖	✖	✖	✖
Autonomy	▲	▲	▲	▲	✔	✖
Mobility	▲	▲	✖	✖	▲	✖
Weighted importance	▲	✔	▲	✔	✔	▲
Probability assignment	▲	▲	▲	▲	▲	▲

8.2 Findings

Confusion still manifests itself in the literature. For example inconsistent terms have been adopted, inconsistent definitions have been used, and partial measurement models proposed.

Contradiction can also be found in inconsistent conclusions obtained in different research papers. For example, it has been proposed that there is an inverse relationship between flexibility and productivity. That means an increase with flexibility will decrease productivity. However, other researchers have concluded that an increase of routing flexibility increases system productivity. Such a contradiction could arise because flexibility attributes have not yet been clearly understood.

There exist trade-offs between the proposed flexibility attributes. It is not possible to increase the flexibility using every attribute, because some of them conflict with each other, e.g., an increase of versatility and variety normally leads to a decrease in the efficiency of the system. Without clarifying its interior conflicts, it can be difficult to explain the reason why the flexibility also conflicts with the other performance parameters.

Some of the conflicts between flexibility attributes are listed as follows:

1. Increase of versatility can lead to decrease of efficiency of the system.
2. Increase of variety sustain versatility; but, decrease efficiency.
3. Increase of autonomy is unnecessary in order to increase the efficiency of the system.

Some other attributes, which have not been explored by the present research, indicate a positive effect on the others:

1. Increase of mobility increases efficiency of the system.
2. Increase in control ability increases efficiency.

3. Increase in learning ability at any system level increases efficiency, versatility, variety, autonomy and mobility.

Flexibility attributes are helpful to production managers in deciding which tasks the company should pursue, e.g., efficiency, versatility, variety, redundancy, autonomy, and/or mobility.

The understanding of flexibility attribute should enable managers to consider the possibility that efficiency is still a core issue to pursue for a company. Improvement of manufacturing flexibility is not the only way of increasing the number of different outputs that the system produces, efficiency consideration should also be included, otherwise, an increase in flexibility will lead to an increase in manufacturing complexity. Consequently, extra costs can arise when flexibility has been introduced.

One reason for the confusion is that researchers have not made boundary conditions clear when they study a given measurement flexibility type. Also there are cases of overlap between different types of flexibility. If they are not precisely identified, confusion will arise immediately.

This thesis has also found that the entropy approach has its limitation in measuring manufacturing flexibility. A revised entropy approach has been proposed by this thesis in Chapter 5.

8.3 Conclusion

The attribute approach proposed in this thesis is mainly for off-line evaluation of flexibility, as the proposals are more concerned with the static stage, rather than dynamic. An on-line evaluation of flexibility using the attribute approach developed in this thesis would require more factors, such as queuing time, waiting time, utilization and reliability of the system, but is still possible. A unified approach to flexibility which includes the static and dynamic components and which is based on the attribute approach given above is now a possibility for the future.

No matter what type of manufacturing flexibility has been chosen for the measurement, it is necessary to define the boundary of application precisely.

Flexibility is vitally important in the current manufacturing environment; but, it makes the system more complicated and difficult to manage. There exists trade-offs in running the business. There has to be a compromise.

The optimum solution to determine the most suitable flexibility level for a system has still to be resolved. The will be impossible if there is no formal method of measurement.

To improve the flexibility of a system it is necessary to identify the core issue. One possibility is the relative role of technology or people. Even though Upton (1995) argued that a high level of computer integration seemed to contribute less to flexibility than people in the paper industry in America, it cannot be denied that technology is still the major means to a higher standard of living.

This thesis gives a unified theoretical framework for manufacturing flexibility measurement which can be applied at any system level and with any flexibility type. This should be verified in future rsearch.

This attribute approach has generated interest in the manufacturing domain. Evidence of this interest and validation of the approach can be concluded from the fact that three papers have been published in International Conference (See Appendix).

There is a need to develop the measurement models with the attribute approach which have not yet been explored in the present research. Those are labour flexibility, and material handling flexibility, belonging to input-orientated flexibility; operation flexibility, and programme flexibility, belonging to process-orientated flexibility; and product flexibility, expansion flexibility, belonging to output-orientated flexibility. The flexibility types mentioned above have attracted less attention than those which have been developed in this thesis. It may be that they are less important than those picked in this research. This does not mean they are not worthy of examination. For instance, labour flexibility plays a vital role in making a system flexible. Also, product flexibility has been a major competitive edge in the marketplace.

An uncertain and dynamic environment has brought about a requirement for a manufacturing system to rely more on flexibility. However, flexibility contained in manufacturing is a multiple attribute concept. It must be carefully examined and implemented, otherwise, an increase in flexibility will lead a company to lose its competitive power. It is sensible to recognize that manufacturing flexibility is not a panacea to production theory and should not be considered to be the only way to compete.

The main omission of the work in this thesis is that it has not yet been applied to real applications. A jobbing shop could be the most suitable case for the study, as every type of flexibility in this thesis can be applied to it using real data so that the various models can be tested including the DEA approach. This practical work is the next step.

Trade-off between flexibility types may exist and which has not been examined by this thesis. It is vitally important to managers to recognize this when implementing flexibility in a manufacturing system.

The attribute measurement models proposed in this thesis for the measurement of flexibility types are only in the initial stage of research and development and still need verification. These could be a useful research task for the future.

In summary, this thesis consolidates and integrates the concept of manufacturing flexibility. Many vague classifications of flexibility types have been clarified and corrected. A unified framework of the attribute approach for each flexibility type has been proposed with mathematical models and accompanying examples. The attribute approach is the underlying theme of this thesis. It is hoped that the work presented here is a useful contribution and that it pushes forward the frontier of knowledge in manufacturing flexibility.

8.4 References

Barad, M. and Sipper, D. (1988), "Flexibility in Manufacturing Systems: Definition and Petri-Nets Modeling", *International Journal of Production Rèsearch*, Vol. 26, No. 2, pp.237-248.

Barad, M. and Sipper, D. (1990), "Flexibility and Types of Changes in FMSs: A Timed Petri-Nets Assessment of Machine Flexibility", *The International Journal of Advanced Manufacturing Technology*, 5, pp.292-306.

Brill, P. H., and Mandelbaum, M. (1989), "On Measurement in Manufacturing Systems", *International Journal of Production Research*, Vol. 27, No. 5, pp.747-756.

Gerwin, D. (1987), "An agenda for Research on the Flexibility of Manufacturing Processes", *International Journal of Operations and Production Management*, Vol.7, No.1, pp.38-49.

Gerwin, D. (1993), "Manufacturing Flexibility: A strategic Perspective", *Management Science*, Vol. 39, No. 4, pp.395-410.

Kumar, V. (1986), "On Measurement of Flexibility in Flexible Manufacturing Systems: An Information Theoretic Approach", in *Proceedings 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: OR Models and Applications*, Ann Arbor, MI, Elsevier Science Publishers, Amsterdam, The Netherlands, pp.131-143.

Kumar, V. (1987), "Entropic Measurement of Manufacturing Flexibility", *International Journal of Production Research*, Vol. 25, No. 7, pp.957-966.

Slack, N. (1983), "Flexibility as a Manufacturing Objective", *International Journal of Production Management*, Vol. 3, No. 3, pp.4-13.

Son, Y. K. and Park, C. S. (1987), "Economic Measurement of Productivity, Quality and Flexibility in Advanced Manufacturing Systems", *Journal of Manufacturing Systems*, Vol.6, No.3, pp.193-207.

Upton, D.M. (1995), "What Really Makes Factories Flexible?", *Harvard Business review*, July-August, pp. 74-84.

Upton, D. M. and Barash, M. M. (1988), "A Grammatical Approach to Routing Flexibility in Large Manufacturing Systems", Journal of Manufacturing Systems, Vol. 7, No. 3, pp.209-221.

Yao, D. D. (1985), "Material and Information Flows in Flexible Manufacturing Systems", *Material Flows* 2 (Special Issue on Flexible Manufacturing System), pp.143-149.

Yao, D. D. and Pei, F. F. (1990), "Flexible Parts Routing in Manufacturing Systems", *IEE Transactions*, Vol. 22, pp. 48-55.